PETROPHYSICAL EVALUATION OF A WELL ON PUNJAB PLATFORM

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Certificate

This thesis is submitted by **Ms. Tabinda Tariq,** and is accepted in the present form by Department of Earth & Environmental Sciences, Bahria University, Islamabad as the partial fulfillment of the requirement for the degree of **Master of Sciences** in **Geology** (1 year program).

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ABSTRACT

Fort Abbas concession is part of Punjab platform, which is a gentle westwardly dipping monocline in the central Indus Basin. The well X-1 was drilled in this concession area on Punjab platform in 1994. The logs were obtained from DGPC. Drilling of this well was carried out to test the hydrocarbon potentials of Kussak and Khewra of Cambrian age and Salt Range Formation of Pre-Cambrian age. Various logs were run in the well for petrophysical evaluation. The basic reservoir parameters were found by using these logs. The well came out to be dry and was abandoned.

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

Pakistan is endowed with three major sedimentary basins (covering more than 2/3 of its total area) namely, Indus Basin , Baluchistan Basin in the west and Pishin Basin in the northwest (Figure 1.1). Indus and Baluchistan Basins are separated by Ornach-Bela transform fault zone and the Pishin Basin lies between Indus and Chaman transform fault (Figure 1.2). A variety of sub-basins, foldbelts and monoclines with variable structural styles resulting from diverse geodynamic conditions have been identified in Baluchistan Basin and Indus Basin. Pakistan is located at the junction of Gondwanian and Tethyan domains. The Indian Ocean and the Himalayas are the most pronounced features of surrounding the Indo- Pakistan subcontinent and they have a common origin. On the basis of plate tectonic features, geological structure, orogenic history and lithofacies, Pakistan is divided into the following broad tectonic zones (Figure 1.3): Indus platform and foredeep, Eastern Balochistan fold and thrust belt, Northwest Himalayan fold and thrust belt, Kohistan Ladakh magmatic arc, Karakoram Block, Kakar Khorasan Flysh basin and Makran accretionary zone, Chagai magmatic arc and Pakistan offshore.

The well X-1, drilled on Punjab Platform (Central Indus Basin) in 1994, has been selected for petrophysical analysis and formation evaluation in this project. X-1 was classified as an exploratory well, but after detailed petrophysical analysis the well was given the status of dry well so it was abandoned. The concession area of this well was Fort Abbas Exploration License. Fort Abbas Block is located in the desert area of Cholistan on the eastern border of Pakistan with India.

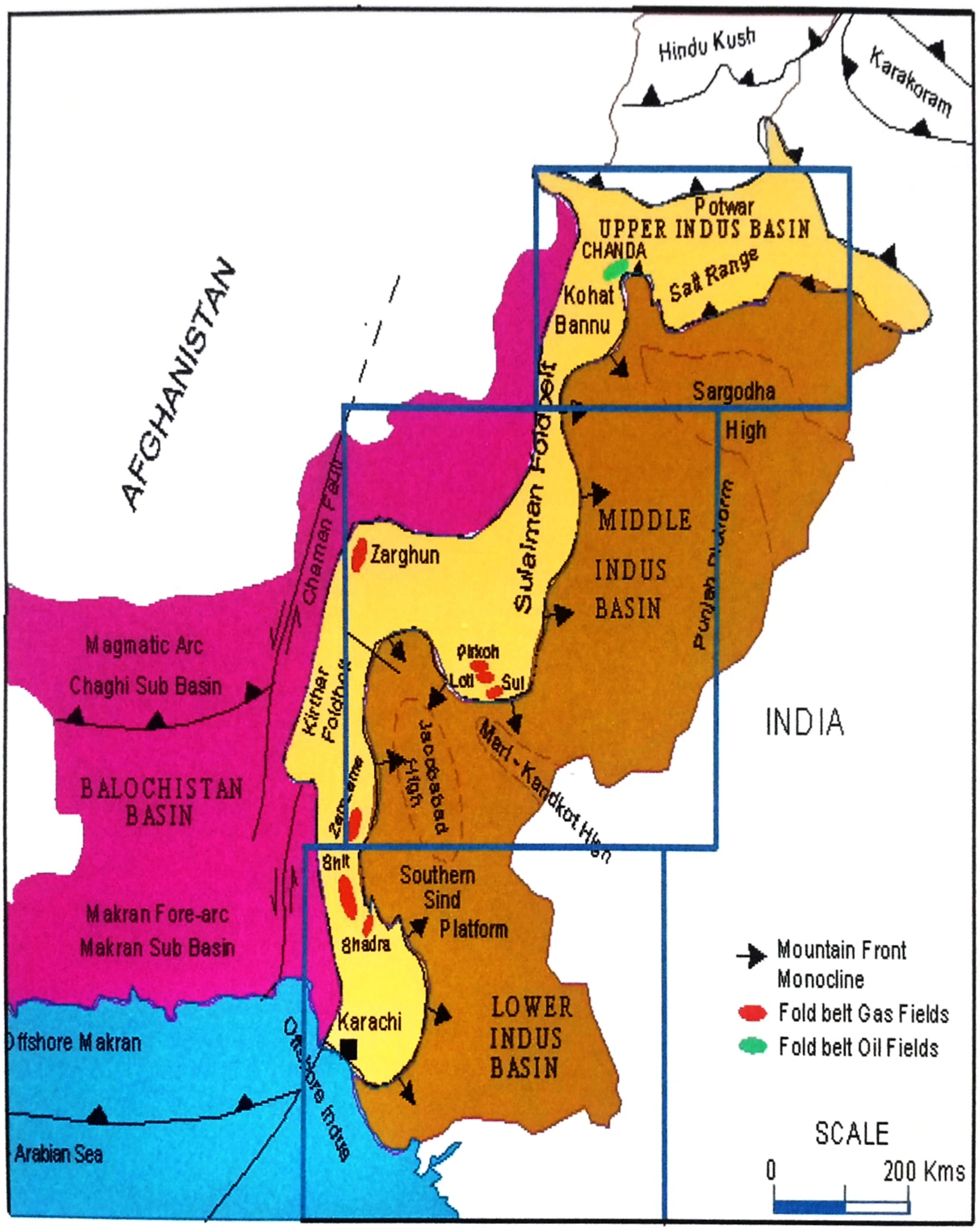


Figure 1.1: Main Sedimentary basins of Pakistan. (After Raza et al. 1989).

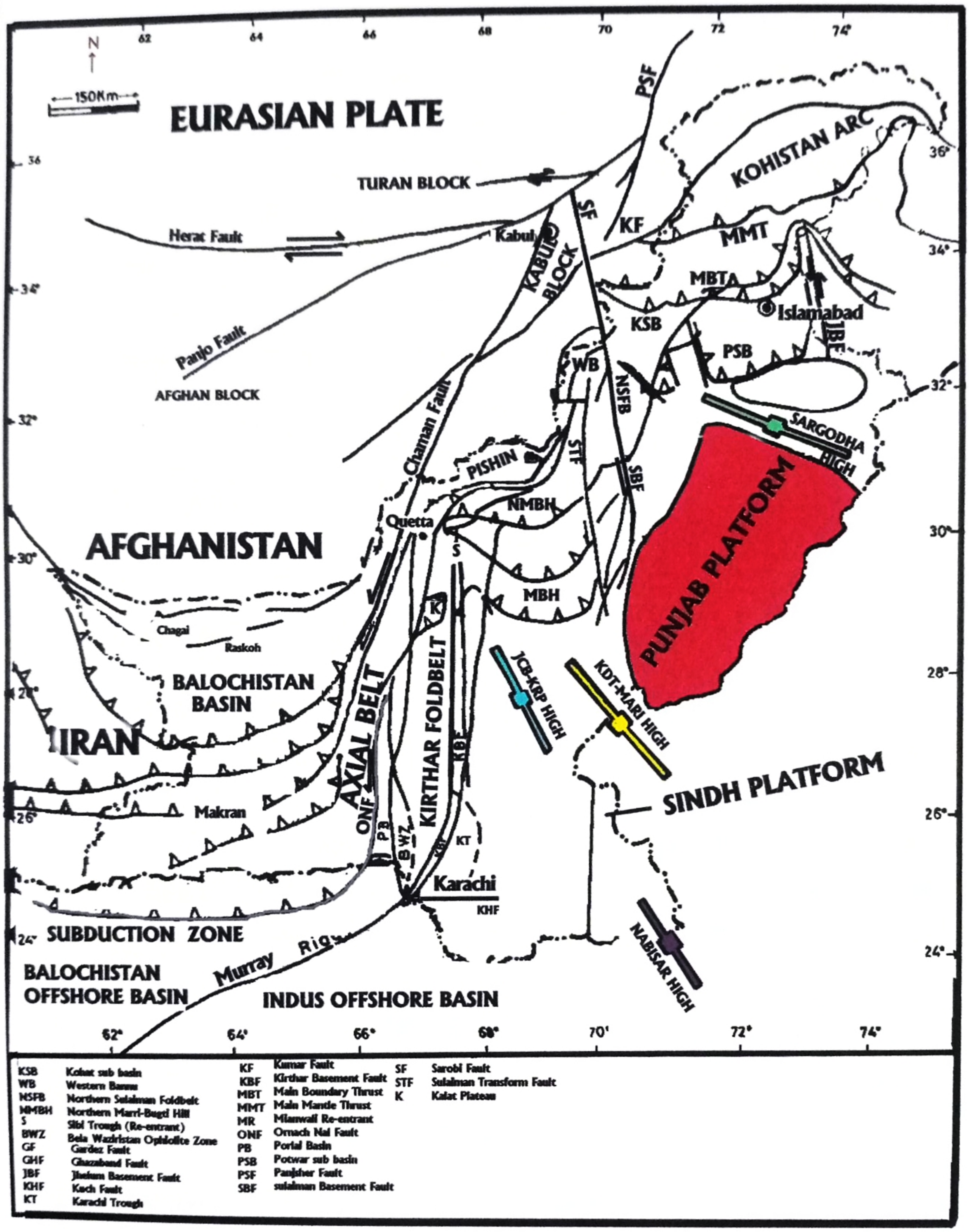


Figure 1.2: Major faults and platforms of Pakistan. Ornach Nal Fault is also marked which separates the Indus and Baluchistan basins (Modified After Mujtaba, 2006).

1.1 INDUS BASIN

The Indus basin covers an area of about 533,500km^2 and contains more than 15,000 meters thick sediments ranging in age form Precambrian to recent. Oil and gas fields have been discovered in the inner folded zones of the Sulaiman and Kirthar Ranges, Kohat-Potwar Plateau, Sulaiman –Kirthar depression (foredeep), Karachi depression, and the Indus platform (Punjab monocline, Sukkur and Sindh monocline) .

The Indus Basin can further be classified as

1. Upper Indus Basin: Kohat sub-Basin
   Potwar sub-Basin

2. Lower Indus Basin: Central Indus Basin
   Southern Indus Basin

1.1.1 UPPER INDUS BASIN

This basin is located in the northern Pakistan and is separated from the Lower Indus Basin by Sargodha Highs (Figure 1.2). Its northern and eastern boundaries coincide with the Main Boundary Thrust (MBT). The Western boundary of the basin is marked by an uplift of Pre – Eocene sediments and eastward directed thrusting to the west of Bannu. The basin is further subdivided into Potwar to the east and Kohat to the west, by river Indus. Regardless of the small size of the Potwar and Kohat sub – basin they depict important facies variations. Both Kohat and Potwar Sub – basins are characterized by an unconformity between Cambrian and Permian.

1.1.2 LOWER INDUS BASIN

The Lower Indus Basin is further sub divided into two parts,

1. Central Indus Basin
2. Southern Indus Basin

The Central and Southern Indus Basin are separated by Jacobabad and Mari Khandkot highs; these are collectively termed as Sukkur Rift (Raza et. al, 1989). Differnt classification schemes have been given to this basin. Two important schemes are given below.

Central Indus Basin: (After Raza et. al, 1984)

a. Punjab Platform

b. Sulaiman Depression

c. Sulaiman Fold Belt

Southern Indus Basin: (After Quadri and Shuaib, 1986)

a. Thar Platform (Sindh Monocline)

b. Karachi Trough

c. Kirthar Foredeep

d. Kirthar Fold Belt

e. Offshore Indus

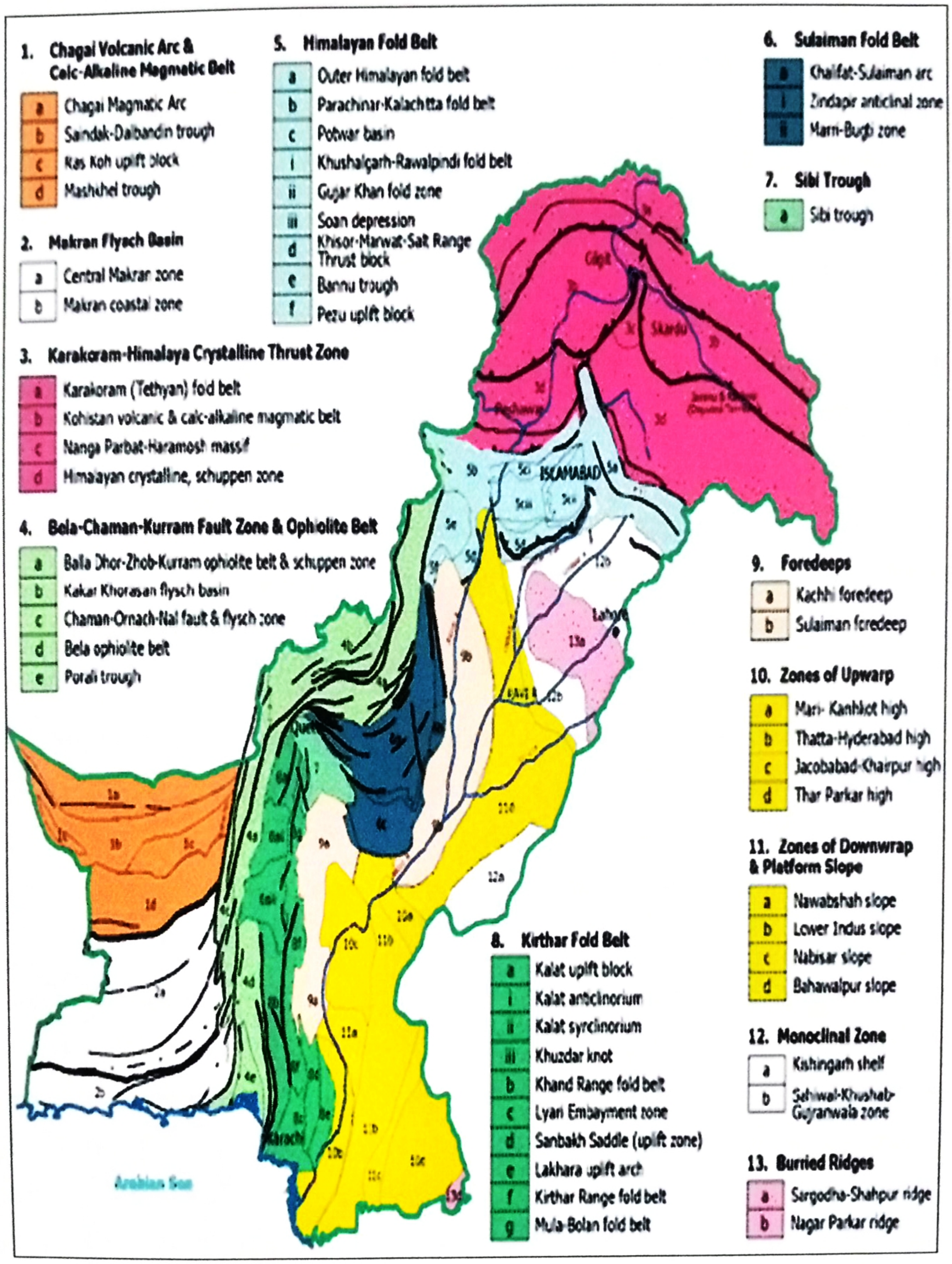


Figure 1.3: Tectonic map of Pakistan showing tectonic sub division of Pakistan (After Kazmi, 1982).

1.2 EXPLORATION HISTORY

Exploration history of the Punjab Platform and the adjoining Bikaner–Nagaur Basin of Indian side, dates back to 1959 when Shell drilled the first exploration well Karampur-1. Heavy asphaltic oil was encountered in Infracambrian reservoirs. Shell subsequently drilled two more wells, i.e., Bahawalpur East-1 and Marot-1 during 1981. Both of the wells were intended to target a base Permian "buried hill". Both the wells encountered the Infracambrian rocks but failed to produce hydrocarbon, possibly due to lack of closure at the Infracambrian level and poor quality of reservoirs. AMACO drilled Sarai Sidhu-1 well in 1974 in which good gas shows were encountered in the Cretaceous rocks.

In 1984-85, Nandpur and Panjpir were discovered by OGDCL as the first (and so far only) gas field of Punjab Platform. The gas, which has accumulated in different Cretaceous and Jurassic formations, has a very high Nitrogen gas (N_2) content.

Discovery of non-biodegraded heavy crude oil at Baghewala-1 in 1991 in multiple zones of the Lower Paleozoic sequences was the first record of oil in the Bikaner-Nagaur Basin on Indian side. The reported reserves are 628 mm bbl. Subsequently three wells were drilled nearby in Pakistan side Punjab Platform, with no commercial success.

Exploration activities accelerated again in the area during the early 1990's when Pakistan Oil Limited (POL) drilled Ahmedpur-1 in 1992 to explore the Cretaceous reservoirs (probably Pab Sandstone pinchout). Oil and Gas Company Limited (OGDCL) drilled Fort Abbas-1 and Bijnot-1 during 1994 and 1996 respectively, to explore the potential of Infracambrian reservoirs in the region. Fort Abbas-1 was not drilled down to the Infracambrian and was plugged and abandoned in the Salt Range Formation. In Bijnot-1, there were some oil shows during drilling but some how the well was not tested on the basis of log results.

In the recent past, OMV drilled Suji-1 in 2000. The well, however, failed to find Infracambrian reservoirs and drilled some 100 m into the basement rocks. Exploration history of the Punjab Platform and the adjoining Indian side indicates that the Infracambrian play in Pakistan has not been properly explored and tested. Only Bijnot-1 seems to be the valid test of the play as it encountered Infracambrian reservoirs in a well defined structural closure. Integration of gravity, magnetic and seismic data of Punjab Platform and Bikaner Basin suggest that wells drilled on paleo-highs are dry mainly due to failure in finding Infracambrain reservoirs.

1.3 WELL X-1

The well X-1 was drilled in Fort Abbas Exploration License which measures 7040.00 Kms^2 in Bhawalpur and Bhawalnagar districts of Punjab Province (Figure 1.4). The well is located in an extreme eastern part of of the Central Indus Basin. X-1 was classified as an exploratory (Wildcat) well.

1.3.1 LOCATION

Fort Abbas structure lies in Bahawalnagar District of Punjab Province. Well X-1 is located in desert area (Cholistan) at a distance of about 28.5 kilometers from Fort Abbas Town and 31 kilometers SE of Marot well. The well is located on tie line of seismic lines 931-FABS-33 and 931-FABS-16A. The well is located at 28° 58' 31" North latitude and 72° 41' 53" East longitude.

1.3.2 OBJECTIVES

The primary objective was the calcareous sandstone of Salt Range Formation of Pre-Cambrian age. The top of this formation was encountered at 1605 m. The secondary objective was sandstone of Kussak and Khewra formations of Cambrian age, the tops of which were encountered at 1335 m and 1500m respectively.

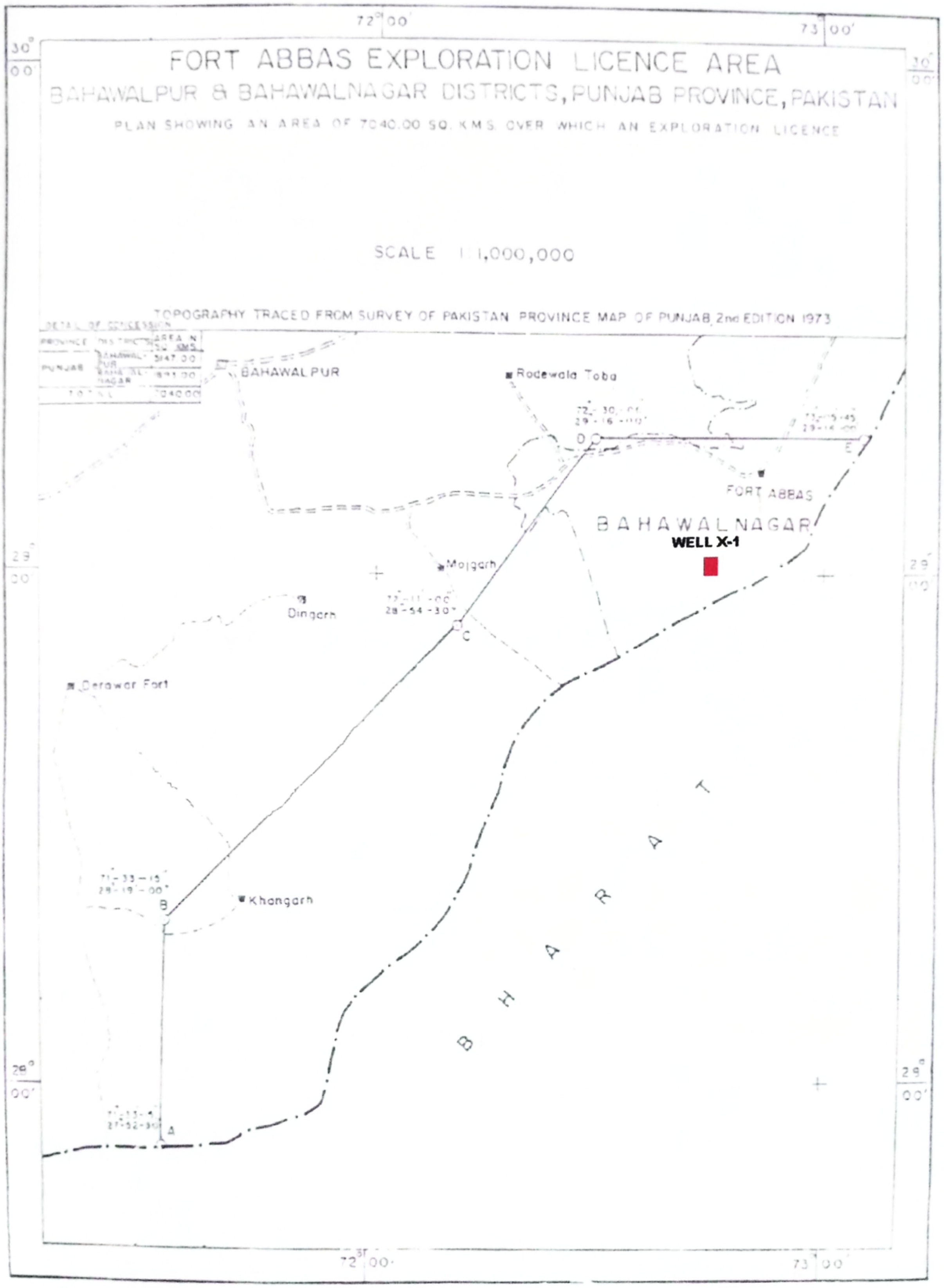


Figure 1.4: The concession map of Fort Abbas Exploration License.

CHAPTER 2

GENERAL GEOLOGY

2. REGIONAL GEOLOGIC SETTING

Middle Indus basin is located in the central Pakistan and is separated from southern Indus Basin by Jacobabad High and Pezu uplift in the north. It is bounded by Indian Shield in the east, marginal zone of Indian Plate in the west, and Sukkur Rift in the south. The oldest rocks exposed in the basin are of Triassic age.

Tectonically middle or central Indus Basin is relatively stable. The basin is comprised of duplex structures characterized by large anticlines and domes in passive roof of sequence of the Sulaiman fold belt, following eastward by gently dipping strata of the Punjab monocline which has few tectonic folds and faults. The basin contains a sedimentary sequence ranging from Precambrian to Recent. It is essentially a natural gas bearing zone and the main producing strata range in age from Cretaceous to Eocene. The basin is characterized by wide variations in geothermal gradients. The geothermal gradient in this zone is relatively high and gas window prevails. So petroleum production is limited to gas and oil gas condensed (Kazmi & Abbas, 2001). The rocks in the subsurface are less deformed and at some places small normal faults are present as indicated by the seismic reflection data

Seismologically the zone is calm and we have only few seismic events. Along the fold belt region the western margin is seismically active and contains a number active faults (Kazmi & Jan, 1997). The Indus platform is covered by unconsolidated Quarternary deposits with the maximum thickness of about 500m. They constitute a vast ground water reservoir. The post Eocene deposits are largely fluviatile and deltaic (Kazmi & Jan, 1997).

2.1 TECTONICS

The Fort Abbas Exploration Licence lies in the Punjab Platform, eastwards of the Central Indus Basin. The Punjab Platform is a gentle monocline. Major part of this platform lies eastward across the political boundary in India, where it is named as Rajasthan Shelf by Verma (1991). Tectonically it is a broad monocline, gently dipping towards Sulaiman Trough.

2.2 PUNJAB PLATFORM

The Punjab Platform, which is a westward dipping monocline, is situated in the Central Indus Basin. It is bounded by Sargodha High in the north, Sukkur rift zone in the south and it merges into Sulaiman depression in the west (Figure 2.1). Despite its large sedimentary area of approximately 60,000 sq km, the exploration activities were marginal, only 18 wells have been drilled so far, which resulted in the discovery of two small gas fields (Nandhpur and Punjpir) in its eastern part.

Recent discovery of oil on commercial scale in the Northern Rajastahan Basin of India has prompted the evaluation of Punjab Platform. Punjab Platform marks the eastern segment of Central Indus Basin. In the east, across the Indian border, Punjab Platform joins Bikaner-Nagaur Basin (Figure 2.2). Tectonically, it is a broad monocline dipping gently towards Sulaiman depression. The Pre-Cretaceous orogenic movements tilted the area eastwards during the Paleozoic, and westward from Mesozoic onwards. The area was relatively less affected by Tertiary orogenic movements because of its greater distance from the collision zone. Therefore, tectonic folds and faults are not abundant and the common structural features are either paleotopographic highs or salt pushed anticlinal folds (Raza et al., 1989). The wells that have been drilled so far on Punjab Platform are shown in Figure 2.2 and a brief summary of these wells is given in Table 2.1

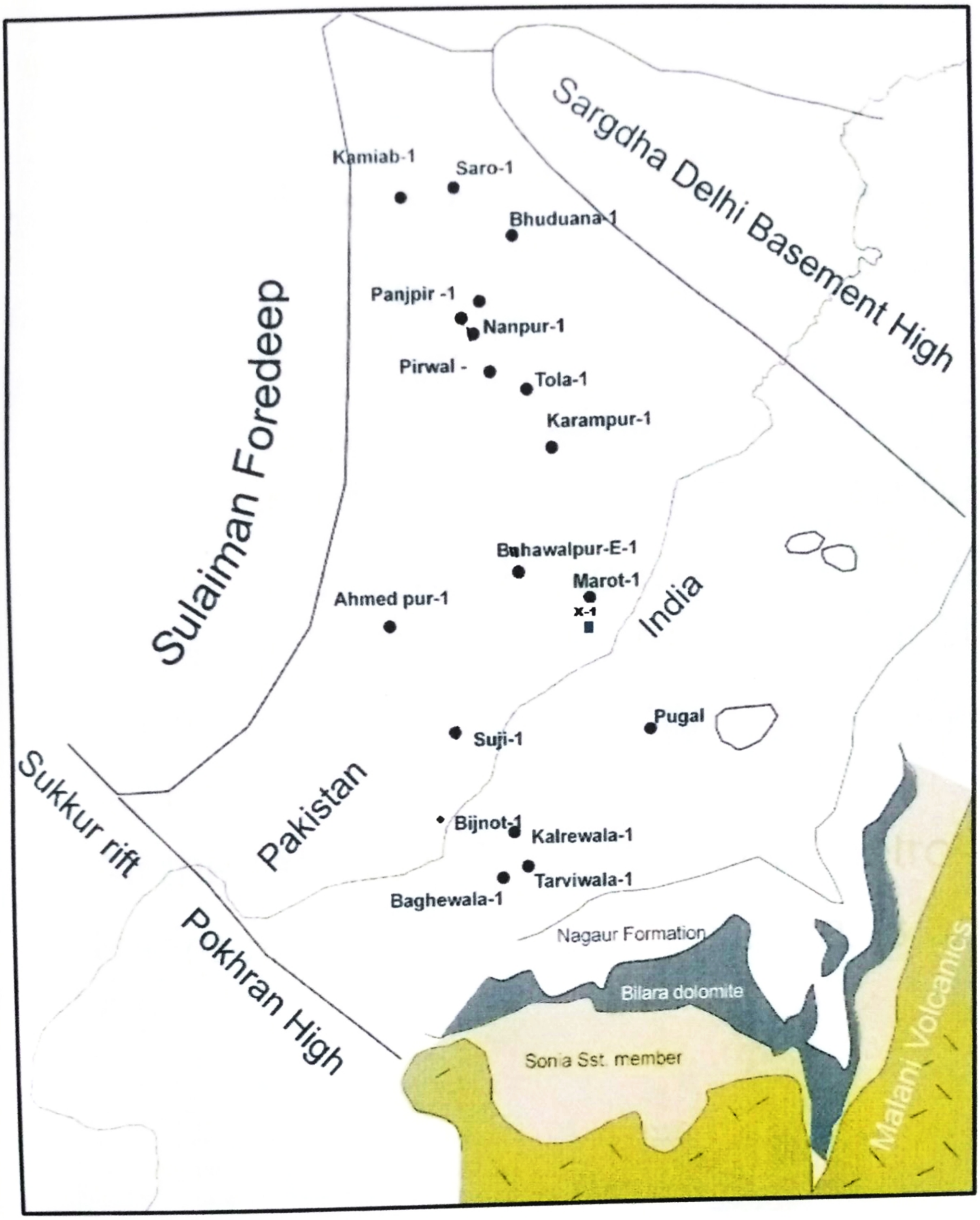
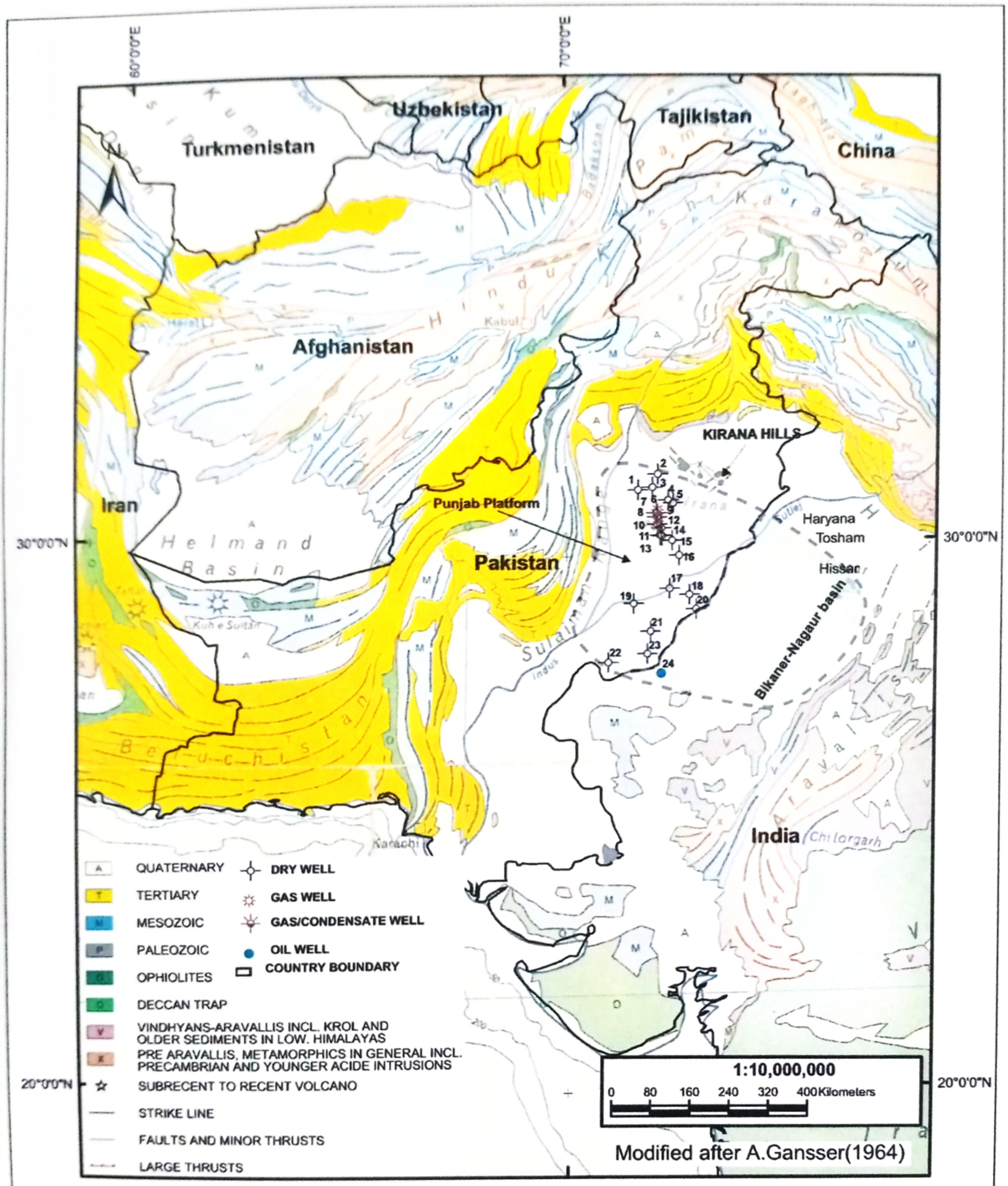


Figure 2.1: Location of Punjab Platform. It is surrounded by Sulaiman Foredeep in the west and by Sukkur rift in the south.



1) Kamiab-1 2) Darbula-1 3) Saro-1 4) Budhuana-1 5) Bagh-X-1 6) Bahu-1 7) Amir Wali-1 8) Jander-1 9) Panjpir-1 10) Sarai Sidhu-1 11) Nandpur-1 12) Ali Sahib-1 13) Chak12-1 14) Piranwal-1 15) Tola-1 16) Karampur-1 17) Bahawalpur East-1 18) Marot-1 19) Ahmedpur-1 20) Fort Abbas-1 21) Suji-1 22) Jiwanwala-1 23) Bijnot-1 24) Baghewala-1

Figure 2.2: Generalized geological map of Pakistan along with wells drilled in Punjab Platform. In the east, across the Indian border, Punjab Platform joins Bikaner-Nagaur Basin.

Table 2.1: Summary of wells drilled in Punjab Platform.

S. NO	WELLS	OPERATOR	YEAR	KBE(M)	TD (M)	TD FORMATION	STATUS
1	KARAMPUR-01	SHELL	1958	142.33	3034.1	Basement	ABD
2	BAHAWALPUR EAST-01	SHELL	1980	135	3024	Basement	ABD
3	MAROT-01	SHELL	1981	143	2596	Basement	ABD
4	BIJNOT-01	OGDCL	1996	129.4	1914	Basement	ABD
5	SUJI-01	OMV	2000	110	2626	Basement	ABD
6	SARAI SIDHU-01	AMOCO	1973	145.26	3279.5	Salt Range	ABD
7	DARBULA-1	OGDCL	1989	184	1550	Salt Range	ABD
8	FORT ABBAS-01	OGDCL	1994	144	1651	Salt Range	ABD
9	BAHU-1	OGDCL	2006	145.6	2936	Salt Range	GAS
10	KAMIAB-01	AMOCO	1974	163.18	2298.4	Samanasuk	ABD
11	PIRANWAL-01	OGDCL	1986	143.7	2581	Baghanwala	ABD
12	TOLA-1	AMOCO	1974	146	1828.7	Warcha	ABD
13	PANJPIR-01	OGDCL	1985	142.3	2120	Tredian	GAS
14	NANDPUR-01	OGDCL	1984	141.5	2110	Kingriali	GAS
15	AMIR WALI-1	OGDCL	2005	144.7	2049	Kingriali	ABD
16	ALI SAHIB-1	OGDCL	2005	142	2052	Kingriali	ABD
17	JANDER-1	OGDCL	2005	143	2055	Kingriali	ABD
18	CHAK-12-1	OGDCL	2006	135	2130	Kingriali	ABD
19	BAGH X-1	OGDCL	2006	148.57	1398	Kingriali	ABD
20	AHMEDPUR-01	POL	1992	114.6	2634	Datta/Shinawari	ABD
21	JIWANWALA-01	OGDCL	1999	131.4	2100	Shinawari	ABD
22	BUDHUANA-01	AMOCO	1974	153.7	1279.5	Samanasuk	ABD
23	SARO-1	OGDCL	1992	166.7	1040	Samanasuk	ABD
24	BAGHEWALA-1	OIL	1991			Basemant	OIL
25	PUGAL-1	OIL	1960			Salt Range	ABD

2.3 STRUCTURE

The structure on which X-1 was drilled is a large anticlinal feature probably formed on a basement high up to the level of top of Pre-Cambrian. It is located in the southwest of Fort Abbas Exploration Licence. During the interpretation of 1374.00 line kilometers of 30 fold vibrosies data of Fort Abbas Exploration Licence, a structure namely Fort Abbas-1 was delineated and drilled in the north of the E.L. A lead also appeared on line 931-FABS-31 which is around 130 Kms, south west of Fort Abbas-1. To confirm the lead, an additional seismic programme of 260 line kilometers was planned and executed. After incorporating the new data, the lead was confirmed and the Bijnot Structure was mapped on the top of Pre-Cambrian level which indicates that it is not complicated. Its amplitude is 80 ms (TWT) while its closed area is about 52 Sq. Kms.

CHAPTER 3

PETROLEUM PROSPECTS

3. PETROLEUM PROSPECTS

The main petroleum prospect in terms of source, reservoir and cap rock is discussed below.

3.1 SOURCE ROCKS

Shales and local origin of organic rich laminated dolomite of Pre-Cambrian age are the main source rocks. These are well developed in this area.
Baghewala Well No 01 of India, located at about 85 Kms south east of X-1 has low maturity heavy oil (API=17.6), generated from Infra-Cambrian source rock. This play may extend into Punjab Platform in Pakistan, where deeply buried Pre-Cambrian to lower Paleozoic section has a maximum thickness of several thousand feet where more mature and significant amounts of petroleum could originate. On the basis of above idea the well X-1 was drilled.

Samples from the Salt Range Formation penetrated in the PSPD (SHELL) wells (Karampur-1, Bahawalpur-1, and Marot-1) were subject to detail source rock evaluation. Their analysis indicated the presence of thin veinlets of black bituminous shales in the Salt Range Formation with low source rock potential. In well X-1 the dolostone and oil shales/coal layers in the interval 1450m-1482m have shown fair to good organic richness. The genetic potential of this interval is good to very good. The level of "Hydrocarbon already generated" is also excellent. The sediments at this depth interval are close to onset of zone of oil generation, but Kerogen type is not known. Sediment logical studies also reveals the presence of only some thin streaks of algal organic matter in Salt Range Formation in this well. According to geochemical analysis carried out by JNOC, the Salt Range Formation in Bahawalpur East-1 contains mainly type IV kerogen.

During drilling of X-1 well, only minute amount of asphalt and oil stains in dolomite samples were recorded. This may also indicate to the above mentioned fact that source potential in Salt Range Formation in this area are also insignificant.

To the south across the border in India heavy crude oil has been discovered at Baghewala well (Figure 3.1). The structure is basement controlled feature and cover large area of about 590 km^2. Heavy crude oil of 19.5 API has been discovered in the Infra Cambrian Jodhpur sandstone and Bilara dolomite equivalent to lower Salt Range Formation. Effective sealing mechanism is provided by a thick salt layer which overlies the reservoir. Most likely the oil has migrated from a mature source rock kitchen lying around the Baghelwala structure which is located updip on a paleohigh. Kalrewala-1 well also produced in this basin towards Indian side.

3.2 RESERVOIR ROCKS

Sandstone of Kussak and Khewra formations of Cambrian age and sparry dolomite with calcareous sandstone of Salt Range Formation of Pre-Cambrian are the main reservoir rocks. The Salt Range Formation has minor shows of heavy oil in Marot-1, Bahawalpur East-1 and Sarai Sidhu-1 wells whereas just across the border in India, Baghewala Well has reserves of heavy oil (API = 17.6) from Pre-Cambrian sandstone and dolomite.

3.3 CAP ROCKS

Intra-formational shales of Kussak and Khewra can act as cap rocks for Kussak and Khewra reservoirs whereas shales of Slat Range Formation may serve as cap rock for Pre-Cambrian reservoir.

3.4 GEOTHERMAL GRADIENT AND SOURCE ROCK MATURITY

An average geothermal gradient of 1.8° has been established for well X-1. Geothermal gradient map of the area reveals that geothermal gradient progressively become lower eastward which correspondingly increases the depth of oil window eastward.

The present day geothermal gradient in the basin appears to be low and for any source rock to get mature. Across the border in India the maximum recorded temperature in an oil well is also 61°C at 1530 m depth i. e 1.8°c/100m. This indicate that, in the past the temperature may have been much higher or more likely a considerable amount of thickness have been removed through erosion during the life of the basin.

3.5 OIL AND GAS SHOWS

No gas shows were observed during drilling. Weak fluorescence was observed in dolomite and sandstone of Salt Range Formation. The direct fluorescence was light brown, orange, un-even and weak. The cut fluorescence was golden yellowish in colour.

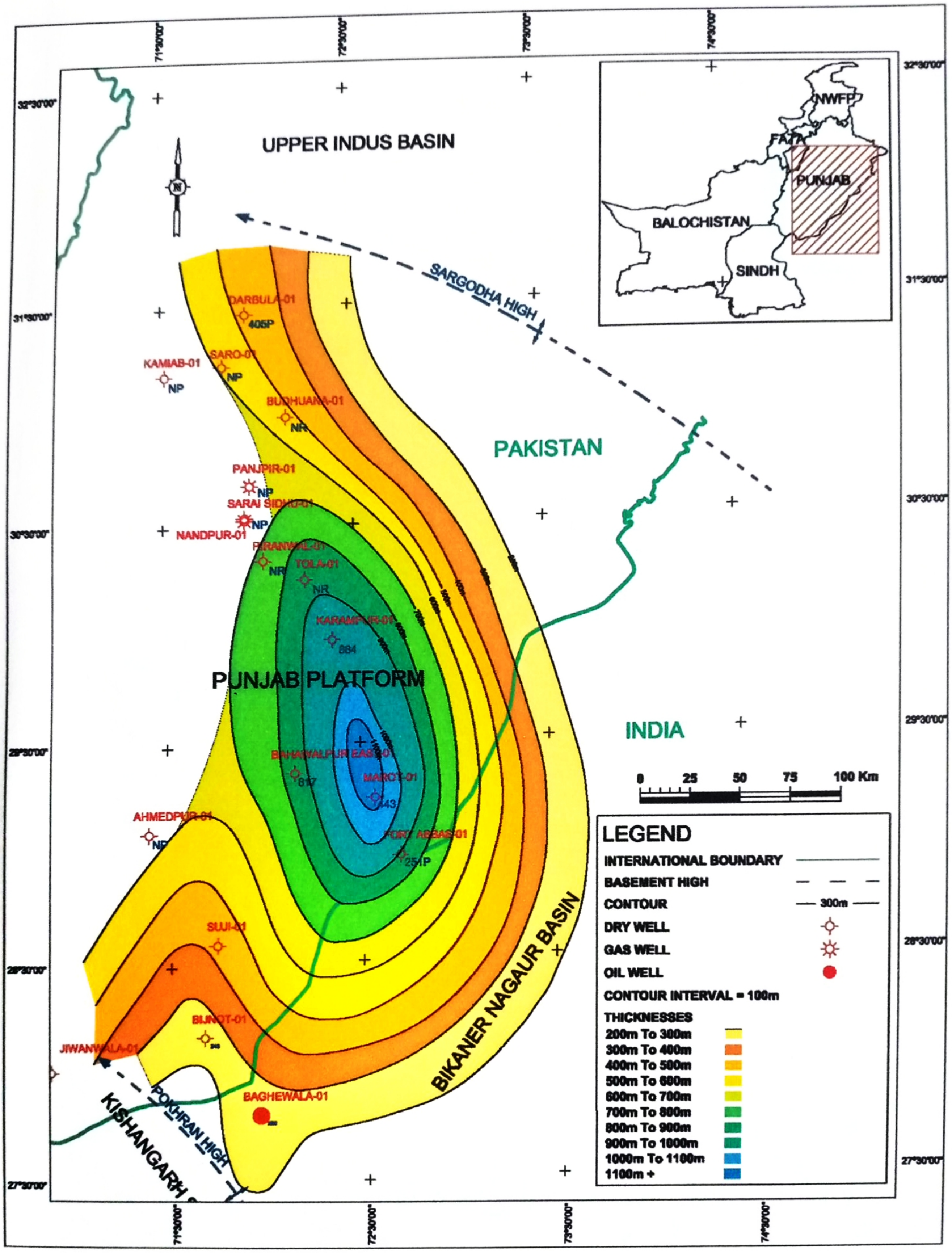


Figure 3.1: Gross thickness map of Infracambrian. Maximum thickness near Marot-1, Bahawalpur East-1 & Fort Abbas-1. The oil well of Baghewala-01 is also marked.

CHAPTER 4

STRATIGRAPHY

4. STRATIGRAPHY

Fort Abbas block was a frontier area in the true scence of exploration. Previous work available was only in the shape of regional seismic lines mostly run by SHELL. There is no previous drilling history within the block. Wells drilled around the E.L are Fort Abbas-1 Bhawalpur-1 Marot-1 and Ahmad Pur East-1 in the north and north west and Sabzal and Sara-1 wells in the south west. The nearest well drilled is in the south across the border in India namely Kalrewala-1 and Baghewala-1. In the Bhawalpur-1, Marot-1, Karampur-1, Beghewala-1 & Bijnot-1 the complete sedimentary cover was drilled to the basement.

During the Pre – Cambrian to Permian time when the Indo Pakistan Plate was part of the Gondwana land. The basement slope was towards east. So was the source of the sediments from west to east. As deduced from the Bijnot well, the basal part has sandstone silt with shale, dolomite & anhydrite inter beds. In the middle is thick salt zone overlain by alternating beds of anhydrite, dolomite & associated shale and sandstone deposited in the restricted marine conditions. In the upper part thick shale zone with minor sandstone & dolomite beds are part of Lower Khewra formation of early Cambrian. Lower Khewra has thick sandstone beds, whereas the Kussak formation represents a mixed lithology of sandstone, shale and dolomite. Mid Cambrian, Jutana formation is a thick dolomite unit followed by sandstone and clays of Baghanwala formation.

The Permian strata succeeds with a marked unconformity represented by a very thick zone of Tillites and Glacial outwash deposits of Tobra formation.

The Tobra formation is succeeded by a very thick clastic sequence of sandstone, clay and silt. The lower part of the clastics may belong to the Lower Permian Warchha and Dandot formations and upper part of Jurassic Shinwari Datta formations. The over lying ooltic carbonate resembles to the Chiltan formations. Limestone is also carbonaceous & sandy and is devoid of any fossils. The Cretaceous sequence is very thin consisting of marl & shale.

The Paleocene sequence is unexpectedly thick in this area composed of Sandstone i.e. glauconitic. Fine to medium grained & fairly sorted. and shales are greenish grey & calcareous. The age is assigned on the basis of Nanno fossils, i.e. Middle to Late Paleocene. The carbonate interval above Paleocene is equivalent to Laki or Sakesar Chorgali formations. It is creamy, off white, crystalline & foramineferal. The age assigned is Early Eocene is unconformable overlain by molasses deposits dominanly consisting sandstone and clay. Figure 4.1 shows a complete stratigraphic succession of the well.

The Punjab Platform contains several tectonic and sedimentary cycles starting from the Infra-Cambrian Salt Range Formation followed by the Cambrian clastic-carbonate-evaporite cycles. The Cambrian cycle is followed by Permian tillite-clastics-carbonate cycle after a long hiatus. A thick Mesozoic sequence is also there. Finally, the Siwalik molasses covers the entire succession.

The lithology as evidenced form flush cutting, along with other mud and drilling parameters, was plotted by wellsite geologist at 1:500 scale on Master Log. The stratigraphic succession was later on established after assimilating all the available data from well site and wireline logs and is summarized in Table 4.1. The correlation of well X-1 with surrounding wells is graphically shown in Figure 4.2.

4.1 SIWALIKS GROUP

The Siwlik group consists of four main formations which are, Chinji, Nagri, Dhok Pathan and Soan. The Chinji formation is of Late Miocene age, Nagri is of Early Pliocene and Soan formation is of Pleistocene age. The contact with underlying Sui Main Limestone Formation is confrmable in the study area. The environment of deposition is fluvial to deltaic. The formation is predominantly comprised of thick sequence of sandstone with interbeds of claystone, whereas occasional thin interbeds of siltstone and limestone (mudstone) were also encountered in the middle part in the well.

Sandstone is whitish grey, grey, greenish grey, loose, sugary, fine to medium grained, sub-angular to sub-rounded, moderately sorted, slightly calcareous and micaceous. Claystone is reddish brown, brick red, soft, gummy, pasty. Siltstone is reddish brown, medium hard, calcareous, partly sandy and grades into fine grained sandstone. Limestone is cream, white, medium hard, microcrystalline, compact, argillaceous and unfossiliferous.

4.2 SUI MAIN LIMESTONE

The Sui main limestone is of Eocene age. The contact with underlying Ranikot Formation is conformable. The environment of deposition is shallow marine.

This formation predominantly comprises of a thick sequence of limestone with interbeds of shale. Limestone is cream, off-white, pale white, medium hard, microcrystalline, compact and highly fossiliferous (foraminifera). Shale is greenish grey, green, soft to moderately indurated, splintery, blocky, pyretic and slightly calcareous.

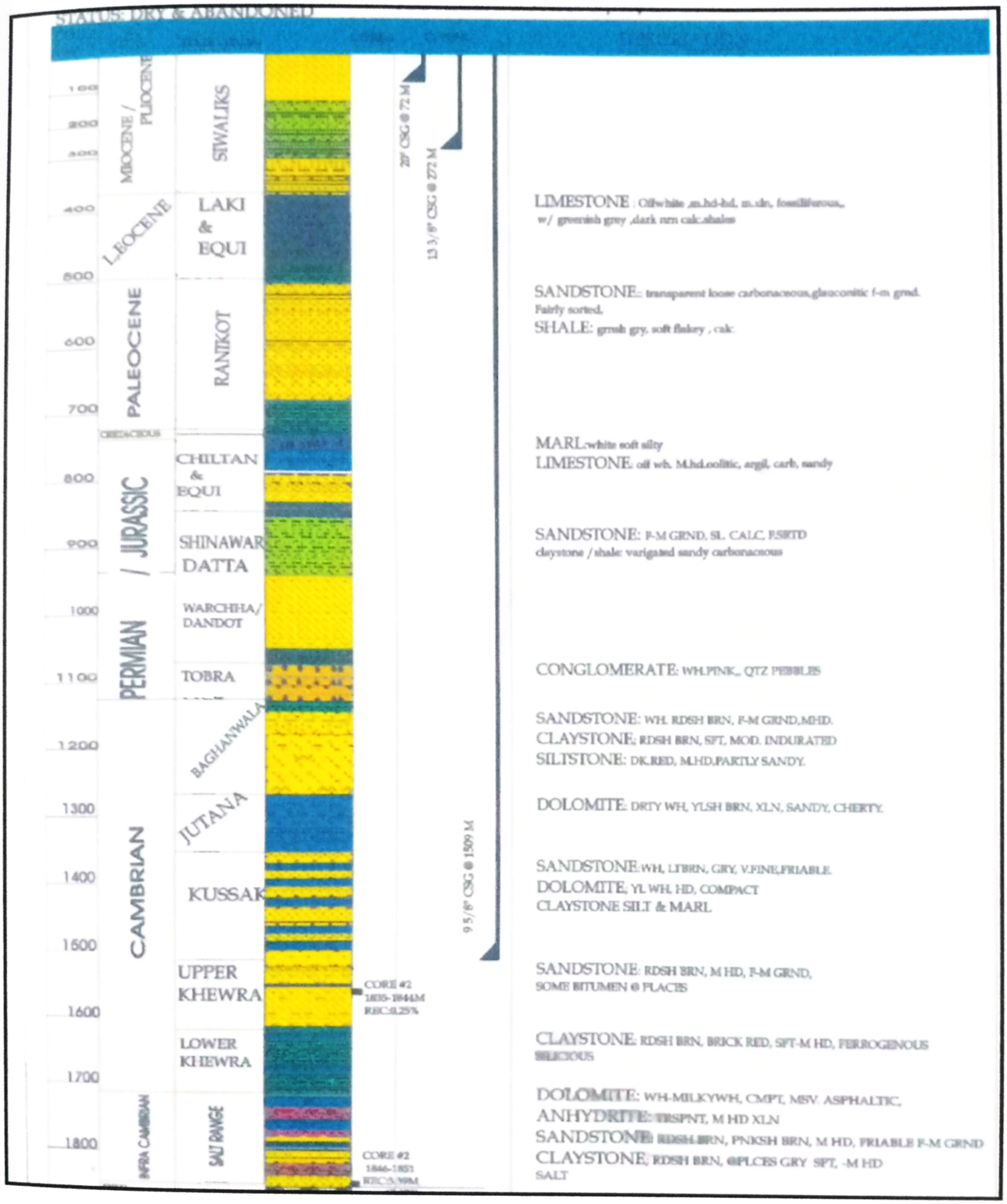


Figure 4.1: Stratigraphic succession of X-1 along with the formation tops encountered. (Adopted from Well completion report, OGDCL).

Table 4.1: Stratigraphic Succession of Well X-1.

AGE	FORMATION	REMARKS
Post Eocene	Siwaliks	Sandstone with interbeds of claystone and occassional thinbands of siltstone and limestone (mudstone).
Eocene	Sui Main Limestone	Limestone with interbeds of shale.
Paleocene	Ranikot	Sandstone with interbeds of shale.
Cretaceous	Mughalkot	Shale.
Cretaceous	Parh	Limestone with interbeds of marl.
Cretaceous	Upper Goru	Marl, limestone and claystone.
Cretaceous	Lower Goru	Sandstone with lateritic claystone at the bottom.
Jurassic	Chiltan	Limestone.
Jurassic	Datta	Sandstone interbedded with clay / claystone.
Permian	Warchha	Sandstone with coal seams, occassional beds of conglomerate and claystone at the bottom of the formation.
Permian	Tobra	Conglomerates with subordinate sandstone and claystone.
Cambrian	Baghanwala	Claystone with thick interbeds of sandstone, thin beds of siltstone and dolomite.
Cambrian	Jutana	Dolomite.
Cambrian	Kussak	Dolomite with subordinate beds of sandstone and thin interbeds of shale, claystone, siltstone and marl.
Cambrian	Khewra	Sandstone with subordinate beds of dolomite and thin interbeds of shale, siltstone and claystone.
Pre-Cambrian	Salt Range	Mixed litho facies like evaporites, claystone, sandstone and siltstone.
Archean	Basement	Rhyolite.

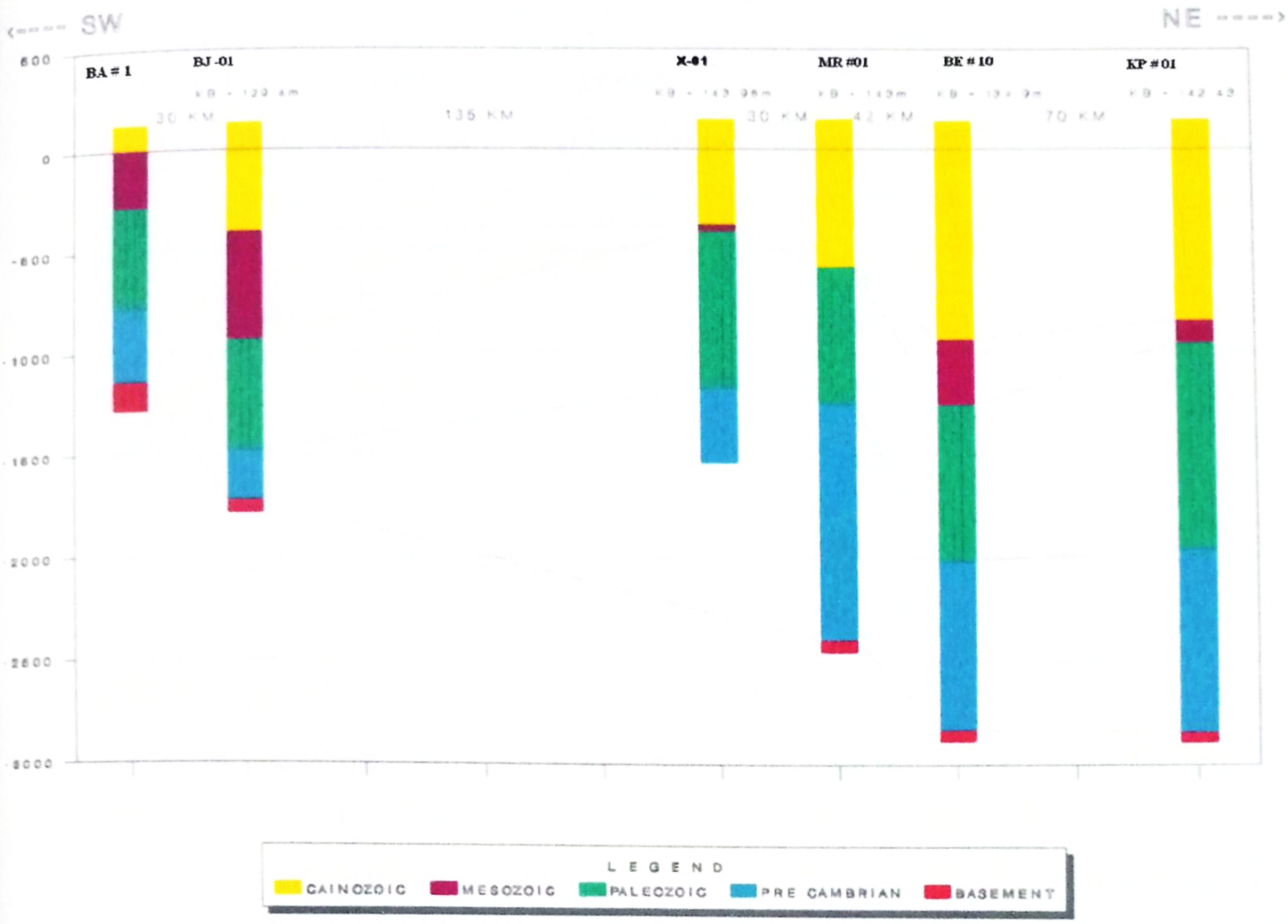


Figure 4.2: Geological Time Scale correlation of X-1 with adjacent wells.

BA #1=Baghewala #1, BJ # 01=Bijnot Well # 01, MR # 01=Marot # 01, BE # 01=Bahawalpur East # 01, Kp # 01=Karampur # 01 (Adopted from ATC proceedings, 2000).

4.3 RANIKOT FORMATION

This formation is of Paleocene age.The contact with underlying Mughalkot Formation is unconformable in the well. These are continental deposits. The Ranikot Formation is dominantly comprised of thick sequence of sandstone with interbeds of shale. Sandstone is light grey, white, whitish grey, loose, medium to coarse grained, quartzose, moderately to well sorted, pyretic, having shell fragments and non-calcareous. Shale is greenish grey, dark grey, black, soft to medium hard, pyretic, glauconitic and carbonaceous (coal laminations).

4.4 MUGHALKOT FORMATION

The age of this formation is Cretaceous. Its thickness at type locality is 70 meters. Its contact with underlying Parh Formation is unconformable. It has a shallow marine depositional environment. This formation is comprised dominantly of shale with traces of sandstone at few places. Shale is grey, dark grey, black, soft, blocky, pyretic and with nodules, highly arenaceous and silty and at some places grades into mudstone.

4.5 PARH FORMATION

The Parh formation is of Cretaceous age. Its contact with underlying Upper Goru formation is transitional. Its environment of deposition is shallow marine. The Parh formation is predominantly comprised of limestone with interbeds of marl. Limestone is off-white, creamy, medium hard, pyritic, cryptocrystalline, locally chalky and rarely fossiliferous. Marl is grey, greenish grey, brownish grey, soft, soluble and lumpy.

4.6 UPPER GORU FORMATION

The Upper Goru formation is of Cretaceous age. Its contact with underlying Lower Goru formation is conformable. This formation is predominantly comprised of marl, limestone and clay. Marl is grey, greenish grey, brownish grey, soft, soluble, sticky, pasty and lumpy. Limestone is grainstone, off white, creamy, medium hard, cryptocrystalline, pyritic and rarely fossiliferous. Clay is lateritic, hemaitic, red to reddish brown, soft, locally indurated, sticky, pasty, noncalcareous.

4.7 LOWER GORU FORMATION

This formation belongs to Cretaceous age. Its contact with underlying Chiltan Formation is unconformable. Its environment of deposiyion is continental deltaic. This formation is predominantly comprised of sandstone with lateritic clay/claystone at the bottom. Sandstone is grey, whitish grey, grayish brown, medium hard, fine to medium grained, sub-angular to sub-rounded, moderately sorted, and slightly calcareous. Lateritic Clay/Claystone is red, reddish brown, earthy, soft to firm, locally indurated and having iron minerals (hematite).

4.8 CHILTAN FORMATION

This formation is of Jurassic age. Underlying contact with Datta Formation is disconformable. The Chiltan Formation consists of limestone. Limestone is dark grey, grey, brownish grey, medium hard to hard, cryptocrystalline, compact, massive, cherty nodules, marly, dolomitic, argillaceous, pyritic, sub-oolitic and non fossiliferous.

4.9 DATTA FORMATION

Datta formation is also of Jurassic age. The contact with underlying Tobra Formation is unconformable. It was deposited in continental environment. The Datta formation dominantly consists of sandstone interbedded with clay/claystone.

Sandstone is quartzose, transparent to translucent, white, whitish grey, dirty white, mainly loose and occasionally friable, fine to medium grained, rarely coarse grained, sub-angualr to sub-rounded, poorly sorted, pyritic, sugary texture and non-calcareous. Clay/Claystone is reddish brown, brown, brownish grey, grey, earthy, soft to firm, arenaceous, hydrophyllic.

4.10 WARCHHA FORMATION

The age of Warchha formation is Early Permian. Underlying contact with Tobra Formation is unconformable. These are Fluviatile deposit laid down in a large alluvial flat. The formation comprises of sandstone with coal seams, occasional conglomerate and claystone at the bottom of the formation.

Sandstone is white to whitish grey, dirty white, medium to coarse grained, at places fine grained, loose, subrounded, quartzose, sugary, transparent, noncalcareous, seams of coal also present. Claystone is reddish brown to brown, soft, sandy, noncalcareous. Conglomerate is white, rounded to sub-rounded, bounded with clay matrix, rarely fossiliferous.

4.11 TOBRA FORMATION

The Tobra formation is of Early Permian age. Its contact with underlying Baghanwala formation is unconformable. The environment of deposition is mainly Glacial. The formation comprises of conglomerates with subordinate sandstone and claystone.

Conglomerates are transparent, white, pinkish white, pinkish, glassy, rounded to sub-rounded, rudaceous clasts bound with reddish clay matrix. Claystone is reddish brown, grey, brownish grey, soft, sandy and non-calcareous. Sandstone is translucent, white, dirty white, pinkish, medium hard, fine to medium granined, at places coarse grained, sub angular, poorly sorted, sugary, quartzose and non-calcareous.

4.12 BAGHANWALA FORMATION

This formation belongs to Middle Cambrian age. The contact with underlying Jutana formation is conformable. Its depositional environment was lagoonal. The Baghanwala formation ormation predominantly consists of claystone with thick interbeds of sandstone, thin beds of siltstone and dolomite.

Claystone is red, reddish brown, brick red, soft, sticky, hydrophyllic and non-calcareous. Sandstone is white, reddish brown, fine to medium grained, medium hard, argillaceous, sub-rounded, at places pyritic and non-calcareous. Siltstone is dark red, medium hard, partly sandy and slightly calcareous. Dolomite is light grey, dark grey, soft, argillaceous and sandy.

4.13 JUTANA FORMATION

The age of Jutana formation is Early Cambrian. The contact with underlying Kussak Formation is conformable. The formation has a shallow marine environment of deposition. The Jutana Formation consists of dolomite. Dolomite is dirty white, yellowish brown, medium hard to hard, massive, cherty, crystalline, argillaceous and sandy.

4.14 KUSSAK FORMATION

This formation is also of Early Cambrian. Its contact with underlying Khewra Formation is conformable. The Kussak Formation predominantly consists of dolomite with subordinate beds of sandstone and thin interbeds of shale, claystone, siltstone and marl.

Dolomite is light grey to grey, dark grey, dirty white, hard, compact and sandy. Sandstone is white, light brown, greenish grey, to light greenish grey, fine grained, friable to medium hard, sub-angularto sub-rounded, moderately sorted, well cemented with argillaceous/siliceous material and dolomitic. Shale is grayish brown, greenish grey, at places grey to dark brown, soft to medium hard, blocky, splintery, glauconitic, arenaceous and dolomitic. Claystone is reddish brown, dark red, soft, sticky and slightly to non-calcareous. Siltstone is dark brownish grey, medium hard, glauconitic, arenaceous and dolomitic. Marl is greenish grey, light grey, soft and soluble.

4.15 KHEWRA FORMATION

This formation belongs to Early Cambrian age. The contact with underlying Salt Range Formation is conformable. It has a lagoonal environment of deposition. The Khewra Formation predominantly consists of sandstone with subordinate beds of dolomite and thin interbeds of shale, siltstone and claystone

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Sandstone is quartzose to wacke, translucent, reddish brown, brown, white, fine to very fine and occasionally medium grained, friable to hard, sub-angular to sub-rounded, moderately sorted, fairly cemented, argillaceous matrix, glauconitic, dolomitic and at places bituminous. Dolomite is yellowish white, light grey, hard, compact, sandy and glaunconitic. Shale is grayish brown, greenish grey, medium hard to soft, blocky to splintery, glauconitic, arenaceous and dolomitic. Siltstone is dard brownish grey, medium hard, sandy, glauconitic, micaceous and dolomitic. Claystone is reddish brown, soft, sticky and non-calcareous.

4.16 SALT RANGE FORMATION

The Salt Range formation is of Pre-Cambrian age. The contact with underlying basement is unconformable. It has a restricted shallow marine and lagoonal environment of deposition. This formation is comprised of mixed litho facies like evaporates, claystone, sandstone and siltstone.

Dolomite is dirty white, white, creamy, medium hard, compact, microcrystalline to crystalline, argillaceous, anhydritic, at places euhedral quartz crystals also exist, sugary texture. Gypsum / Anhydrite is transparent to opaque, glassy, white, light grey, greenish grey, soft to medium hard and crystalline. Claystone is reddish brown, rusty red, grey, brick red, dull, soft to medium hard, ferruginous, at places highly, gypsyferous nature, dolomitic and occasionally of marly nature. Sandstone is pinkish, reddish brown, transparent to translucent, medium hard to friable, coarse to very coarse grained, rounded, moderately sorted, red clay matrix and having calcareous cement.

CHAPTER 5

LOGGING TOOLS AND THEIR PRINCIPLES

5.0 FORMATION EVALUATION

Formation evaluation is the process of using bore hole measurement to evaluate the characteristics of sub-surface formation. These measurements may be grouped together into four categories:

1. Master & Mud logs
2. Core Analysis
3. Wireline Logs
4. Productivity Tests: eg, DST & production testing

All these measurements and data have their own significance and special applications; nevertheless, they all have a common objective of evaluating the formation for:

1. Identification of reservoir.
2. Estimation of hydrocarbons in place.
3. Estimation of recoverable hydrocarbon.

5.1 WIRELINE LOGGING

Well logging is the process of recording various physical, chemical, electrical or other properties of the rock/fluid mixtures versus depth penetrated by drilling a well. So, well logs or wireline logs are continuous recordings of well depth versus different petrophysical characteristics of the rocks through which the well is drilled. There are many types of well logs.

Log interpretation has outgrown the primitive status of being merely a method for discriminating between hydrocarbons and water. Modern log data has become the major input into the evaluation of formation characteristics, whether it be in an open or cased hole, an exploratory, development or producing well. Along with wire line logging, there are many other methods available for use in Formation Evaluation such as Core Analysis, Drill Stem Test. (DST), Repeat Formation Test (RFT), etc. (Schlumberger, 1990).

5.2 LOGGING ENVIRONMENT

Whenever we record and produce a well log, the logging device basically responds to two sets of interacting variables or conditions in the borehole and adjacent geological formations; they are as listed below.

5.2.1 THE GEOLOGICAL ENVIRONMENT

Geological environment consists of the rock and reservoir properties in the geological section, which are a function of three sets of variables:

1. Bedding or layering in a stratigraphic sections i.e the order and amount of different types of rock.
2. Composition of individual rocks i.e. the compositional, chemical and physical properties of the mineral grains in each rock.
3. The type of the fluid i.e. the chemical and physical properties of the fluid distributed in the pore space.

The logging tool during a logging operation encounters a variety of geological conditions and responds accordingly to the particular rock characteristics. Because rock characteristics in nature are highly variable and complex. We should bear in mind, when interpreting the logging tool response, that even the minor details if not understood and accounted for could lead us to an absolutely false conclusions. It is therefore necessary to have a good idea of the geological environment that the logging devices are going to be exposed to and have a fairly good understanding of the rocks constituting the environment. The relevant information about the formation being drilled can be obtained from the well site geologist's cuttings or core logs and reports. Logging operation can cover a wide range of measurements and surveys but they are costly. Obviously, not all the measurement is needed on every well. It is most important to have a good understanding of the geological conditions expected to be encountered and to design the logging program to evaluate the formations in the most effective and economic way.

5.2.2 BOREHOLE ENVIRONMENT

The bore hole environment is created by drilling process (Figure 5.1). The physical distortions introduced into a geological section are a function of at least three sets of distinct variables:

1. Mechanical alteration of rock by drilling process.
2. Alteration of fluid distribution within the rock pores.
3. Mechanical alteration of the bore hole geometry by the circulating mud.

The reservoir rock is composed of porous hydrocarbon bearing rock. The rock matrix is made up of grain of sandstone,limestone,dolomite or mixture of these rocks. Between the grains is pore space filled with water, oil or gas. These components may exist together or may occur singularly. The pore space occupied by these components depends upon the concentration of each of the individual components.

When the bore hole is drilled in a formation the rock and the fluid in the rock undergoes alteration in the vicinity of the bore hole. All logging measurements are then affected by the bore hole and the altered rock around it.

5.3 BORE HOLE CONDITIONS

Bore hole conditions affecting the log measurement are:

1. Bore Hole size
2. Drilling mud
3. Mud cake
4. Mud filtrate

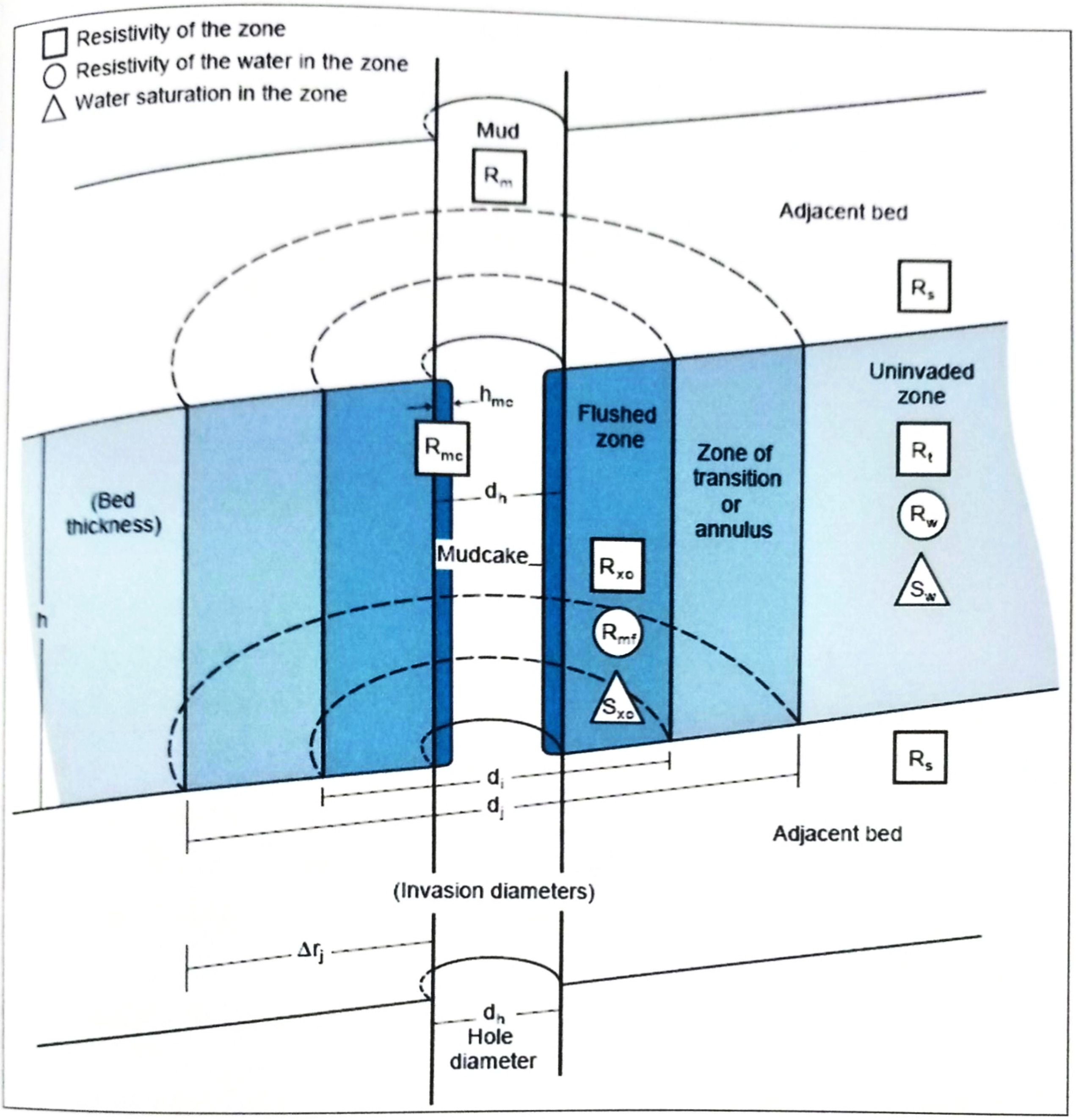

Figure 5.1: The general Borehole environment along with the basic symbols used in log interpretation. (Courtesy Schlumberger)

Some important terms used in studying borehole environment (Figure 5.1) and log interpretation are given below:

1. d_h Borehole diameter
2. *di* Average diameter of invaded zone
3. dj Average outer diameter
4. *h* Bed thickness in meters
5. *Rm* Resistivity of the mud
6. *Rmf* Resistivity of the mud filtrate
7. *Rmc* Resistivity of the mudcake
8. *Rw* Resistivity of the formation water
9. *Rwa* Apparent resistivity of the formation water
10. *Rt* Resistivity of the formation (uncontaminated zone)
11. *Ro* Resistivity of the formation when 100% water filled
12. *Rxo* Resistivity of the flushed zone (close to borehole)
13. *Rsh* Resistivity of the shales
14. *Sw* Water saturation, percent of pore space occupied by water
15. *Sxo* Water saturation in flushed zone or invaded zone

5.3.1 BORE HOLE SIZE (d_h)

The normal size of the hole is taken to be the outside diameter measurement of the drilling or coring bit used to make the hole. Holes are seldom smooth and straight like a "rifle barrel". Sloughing of shales and collapse of unconsolidated sediments create "over gauge" or oversize holes. Buildup of mud cake on the more porous and permeable rocks creates "under gauge" or undersize holes. Some low porosity rocks such as dense limestone and hard cemented sandstones will have a borehole diameter roughly equal to bit size.

However, the bore hole is seldom perfectly circular, it is usually elliptical due to the removal of more material in the direction of least subsurface stress.

5.3.2 DRILLING MUD

The main functions of the drilling mud are:

1. To carry rock cutting to the surface
2. To prevent the uncontrolled escape of formation fluids
3. To lubricate and cooling of drill string

The hydrostatic pressure of the drilling fluid must be greater than the formation pressure otherwise a blowout could occur against a productive interval. This overbalanced system allows for the entry of mud fluids into the pore spaces of the permeable rocks. It is this invasion of mud fluid into the reservoirs that affects the logging tools response. The mud is weighted up with clay usually bentonite and other additives are used to give specific properties to the mud.

5.3.3 MUD CAKE

Mud cake forms usually within the first few minutes of the formation being penetrated. Clay particles are caked against the side of the bore hole and effectively seal off the formation to further invasion. Invasion takes place continuously as the hole is deepened because the mud cake becomes damaged or is removed by drilling, logging or testing tools. Thick mud cake affects the readings of shallow investigation logging tool. The presence of mud cake, however, is usually a good indication of a permeable rock.

5.3.4 MUD FILTRATE

Fluid which enters permeable zones from the mud, is called mud filtrate.The filtrate is usually water in the normal mud system and its resistivity is dependent on the original salinity of the mud system. All logging tools are affected to some degree by mud filtrate.

5.4 INVASION

During drilling the mud pressure in the annulus must be kept greater than the hydrostatic pressure of fluid in the formation pores to prevent a well blowout. The differential pressure which is typically a few hundred psi, forces drilling fluid into the formation. As this happens solid particles in the drilling mud plate out on the formation wall and form a mud cake.

Liquid that filters through this mud cake, the mud filtrate, passes into the formation and pushes back some of the reservoir fluids there. In this way, an invaded zone is formed adjacent to the bore hole.

5.5 INVASION PROFILES

5.5.1 FLUSHED ZONE

Adjacent to the borehole the invasion process flushes out the original water and some of the hydrocarbons (if any were present). This zone is known as the flushed or invaded zone (Figure 5.1). The resistivity of this zone is termed R_{xo}; the water saturation is called S_{xo}.

5.5.2 TRANSITION ZONE

Further from the borehole the flushing action of the mud filtrate may create a variety of situations. If the flushing proceeds as a uniform front, we call this a step profile of invasion. If the intermingling of formation fluids is gradual, we call this a transition zone. Sometimes in oil- or gas-bearing formations, where the mobility of hydrocarbons is greater than the connate water, the oil or gas move out leaving an annular zone filled with connate water.

5.5.3 UNINVADED ZONE

This is the zone that we want to analyze—it is the formation undisturbed by the drilling process. Its resistivity is termed R_t, water resistivity R_w and water saturation $S_{w.}$

5.6 RESISTIVITY CONCEPT

In log evaluation the resistivity of the formation is the principal indicator of hydrocarbons, therefore emphasis has been put on the precise determination of resistivity. The resistivity of a formation depends on amount of water present and pore structure geometry.

5.6.1 PRINCIPLE

Formation resistivites are measured by either sending current into the formation and measuring the ease of the electrical flow through it or by inducing an electric current into the formation and measuring how large it is. Formation resistivities are usually from 0.2 to 1000 ohm-m. Resistivities higher than 1000 ohm-m are uncommon in permeable formations but are observed in impervious, very low porosity formations (e.g., evaporites).

That is why quite a number of tools and techniques have been designed and developed to make very accurate measurements of this parameter.

5.7 TYPES OF RESISTIVITY TOOLS

Various types of laterologs and induction logs are currently in the use. Some commonly used tools have been explained in the proceeding sections.

5.7.1 LATEROLOG DEEP (LLD)

Laterolog tool (Figure 5.2) are generally used for:

1. High resistivity formation
2. Saline muds

Laterologs emit focusing currents to direct the path of the measured current through the mud and the invaded zone to the uninvaded formation. They reduce the effects of the borehole adjacent formations and thin beds, but are still affected by hole diameter, mud resistivity and very thin formations with high resistivity contrasts between beds. LLD (Figure 5.3) is a deep resistivity tool which measures R_t in undisturbed zone.

Both LLD and LLS use the same elctrodes and have the same current beam thickness, but have different focusing to provide their different depth of investigation characteristics.

5.7.2 LATEROLOG SHALLOW AND MSFL

The dual Laterolog (DLL) consists of two advanced laterolog tools, which share the same electrodes on the primary sonde. One laterolog is used for deep investigation of the undisturbed zone (R_t) and the other for shallow investigation of the transition zone (R_i).

A Microspherically Focused Tool (MSFL) on an optional secondary sonde, that measures flushed zone resistivity and permits the deep laterolog to be corrected for invasion. Gamma Ray, SP and Caliper curves may also be recorded with these tools.

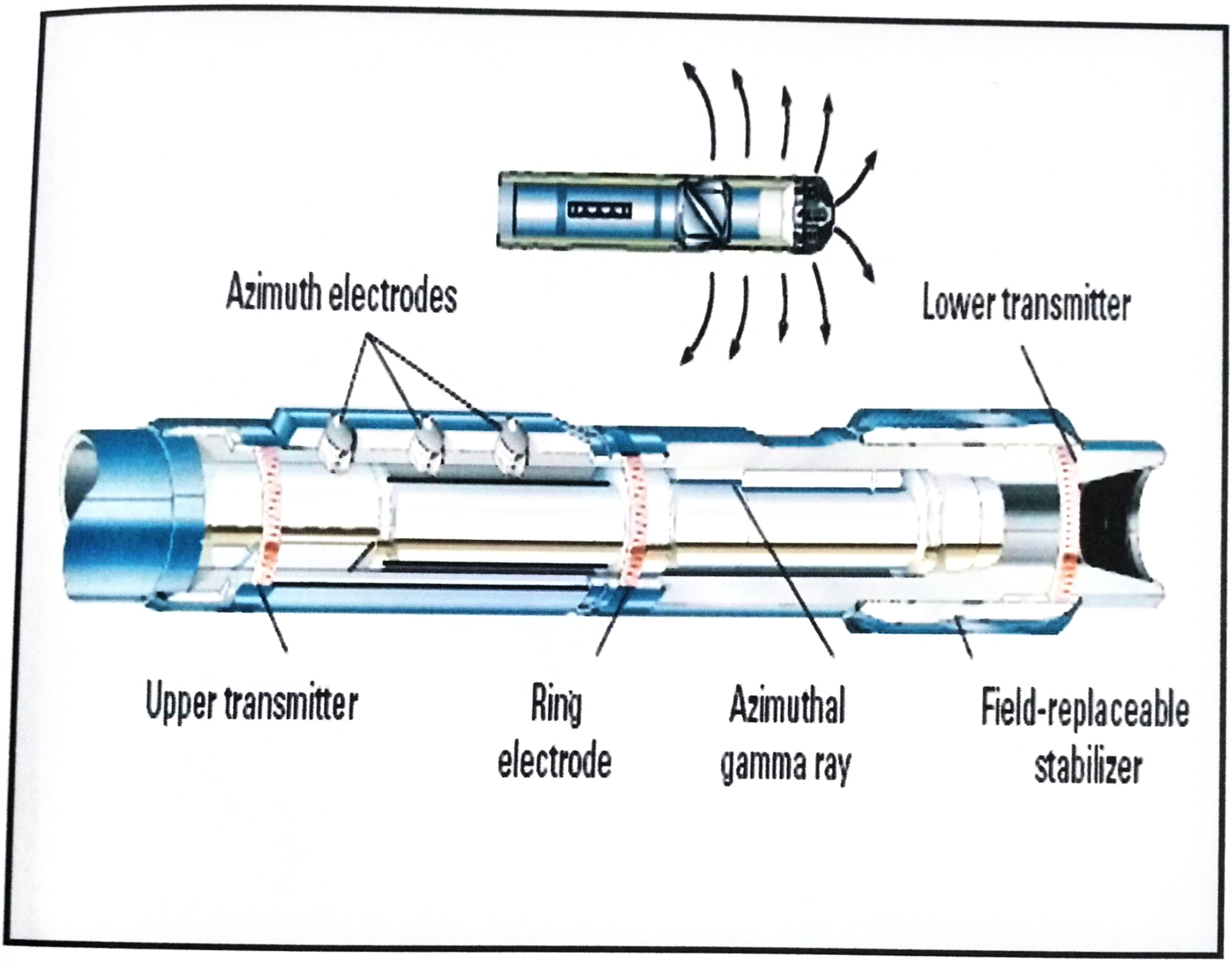

Figure 5.2: A laterolog tool assembly. The sensors include ring & bit resistivity and three azimuthally oriented for imaging capabilities with downhole processing.

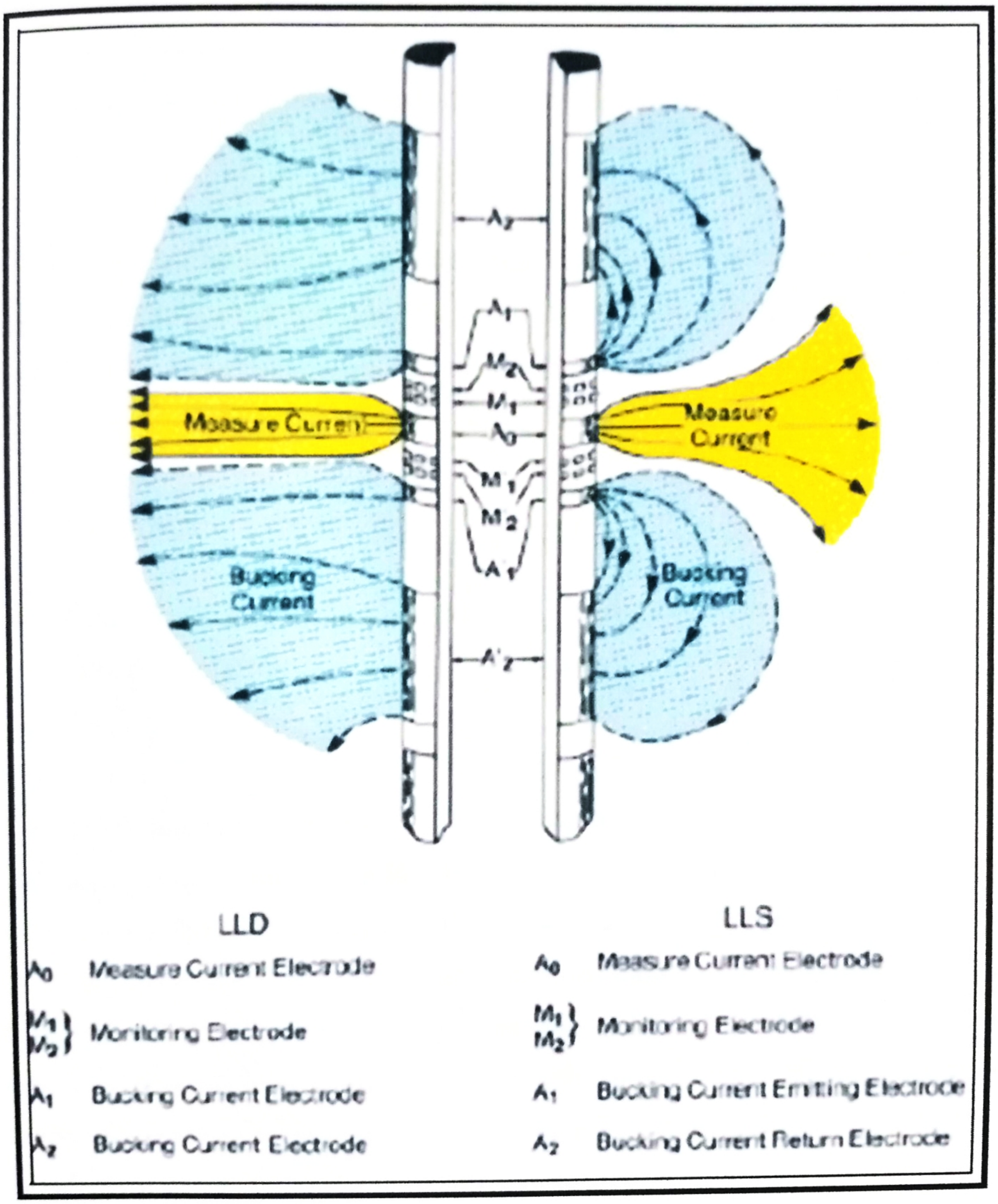

Figure 5.3: Dual Laterolog deep and shallow current patterns.

5.7.3 INDUCTION LOG

The induction logging tool was originally developed to measure formation resistivity in boreholes containing oil-base muds and in air-drilled borehole. Electrode devices did not work in these nonconductive muds, and attempts to use wall-scratcher electrodes were unsatisfactory.

They induce measured currents to the formation, which are focused both horizontally and vertically. The readings of 'R_t'are good for conditions of relatively shallow invasion and thick beds. However, these tools are less satisfactory when the bed thickness is only a few feet or when formation resistivities are over 100 ohmm.

5.7.3.1 PRINCIPLE

Today's induction tools have many transmitter and receiver coils. However, the principle can be understood by considering a sonde with only one transmitter coil and one receiver coil (Figure 5.4)

A high-frequency alternating current of constant intensity is sent through a transmitter coil. The alternating magnetic field created induces currents in the formations surrounding the borehole. These currents flow in circular ground loops coaxial with the transmitter coil and create, in turn, a magnetic field that induces a voltage in the receiver coil. Because the alternating current in the transmitter coil is of constant frequency and amplitude, the ground loop currents are directly proportional to the formation conductivity. The voltage induced in the receiver coil is proportional to the ground loop currents and, therefore, to the conductivity of the formation.

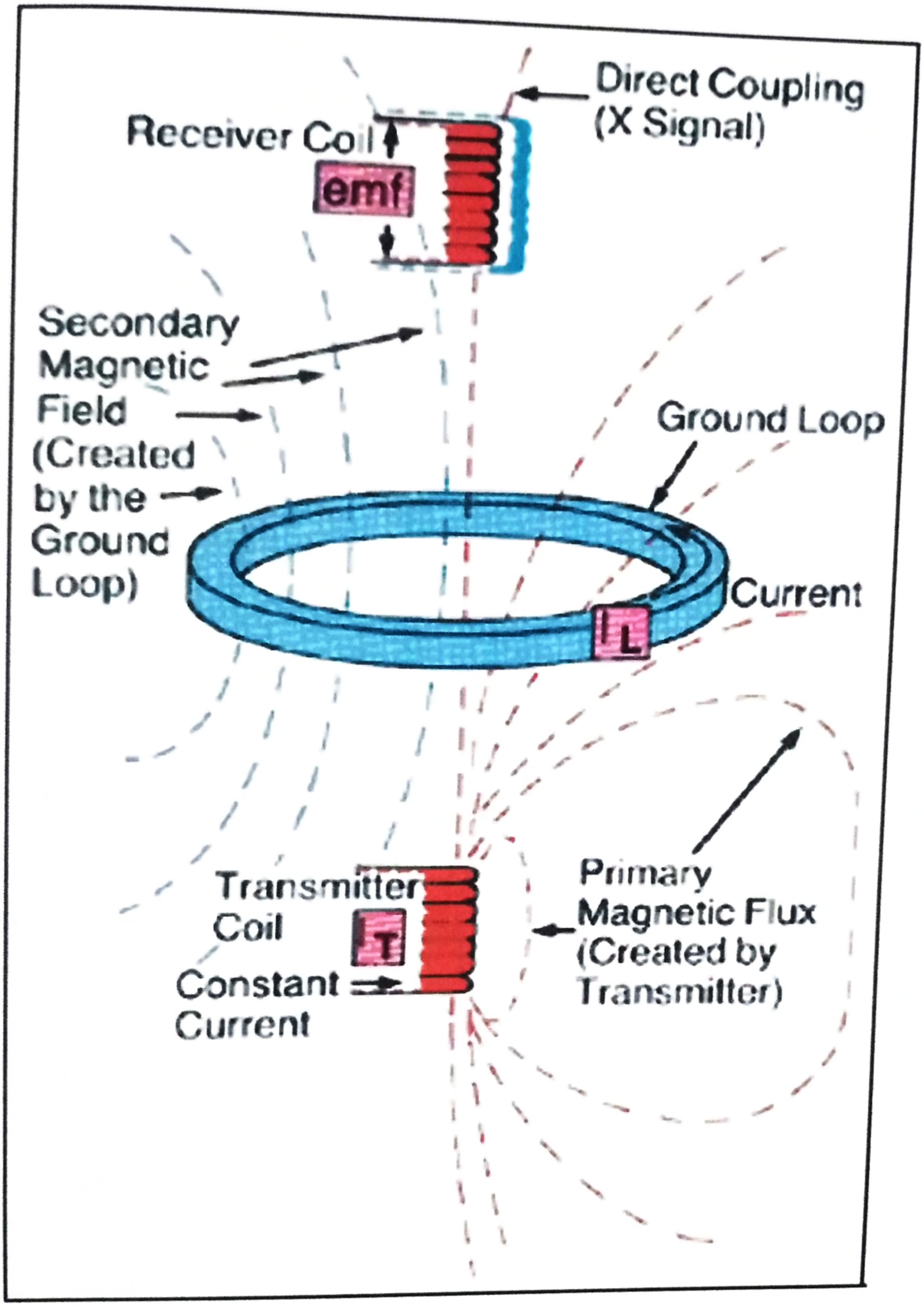

Figure 5.4: The basic two-coil induction log system.

5.7.3.2 DUAL INDUCTION SPHERICALLY FOCUSED LOG

This is the most basic of induction devices and was the reference resistivity induction device for more than 20 years until its retirement in 1990. The tool (Figure 5.5) supplies three focused resistivity curves: two induction and a shallow investigating spherically focused curve plus the spontaneous potential (SP). Each curve (Figure 5.6) has a different depth of investigation. The basic logs recorded by this tool are given below.

1. **Spherically focused log**—a shallow reading device affected mainly by the flushed (R_{xo}) zone (radial distance 30 cm).
2. **Medium induction (ILM)**—depending on the invasion diameter and profile the ILM may be influenced by the R_{xo} or R_t zones or both (radial distance 60 – 80 cm).
3. **Deep induction (ILD)** —mostly affected by R_t, unless invasion is very deep. Either or both induction curves may be influenced if an annulus is present (radial distance 1.2 – 1m).

5.8 SONIC (ACOUSTIC) LOG

The sonic log is a recording of time (D_T) in microseconds vs depth for a sound wave to cross one foot of formation along a path parallel to the well bore.

The sonic travel time is a function of formation lithology and porosity. The Sonic velocity log was originally developed as an aid in the interpretation of seismic data, but it has been found so effective in the determination of porosity that it has now become the standard wire line tool for porosity estimation, fracture and lithology determination. It is also an excellent tool for correlation especially used in conjunction with the Gamma Ray log.

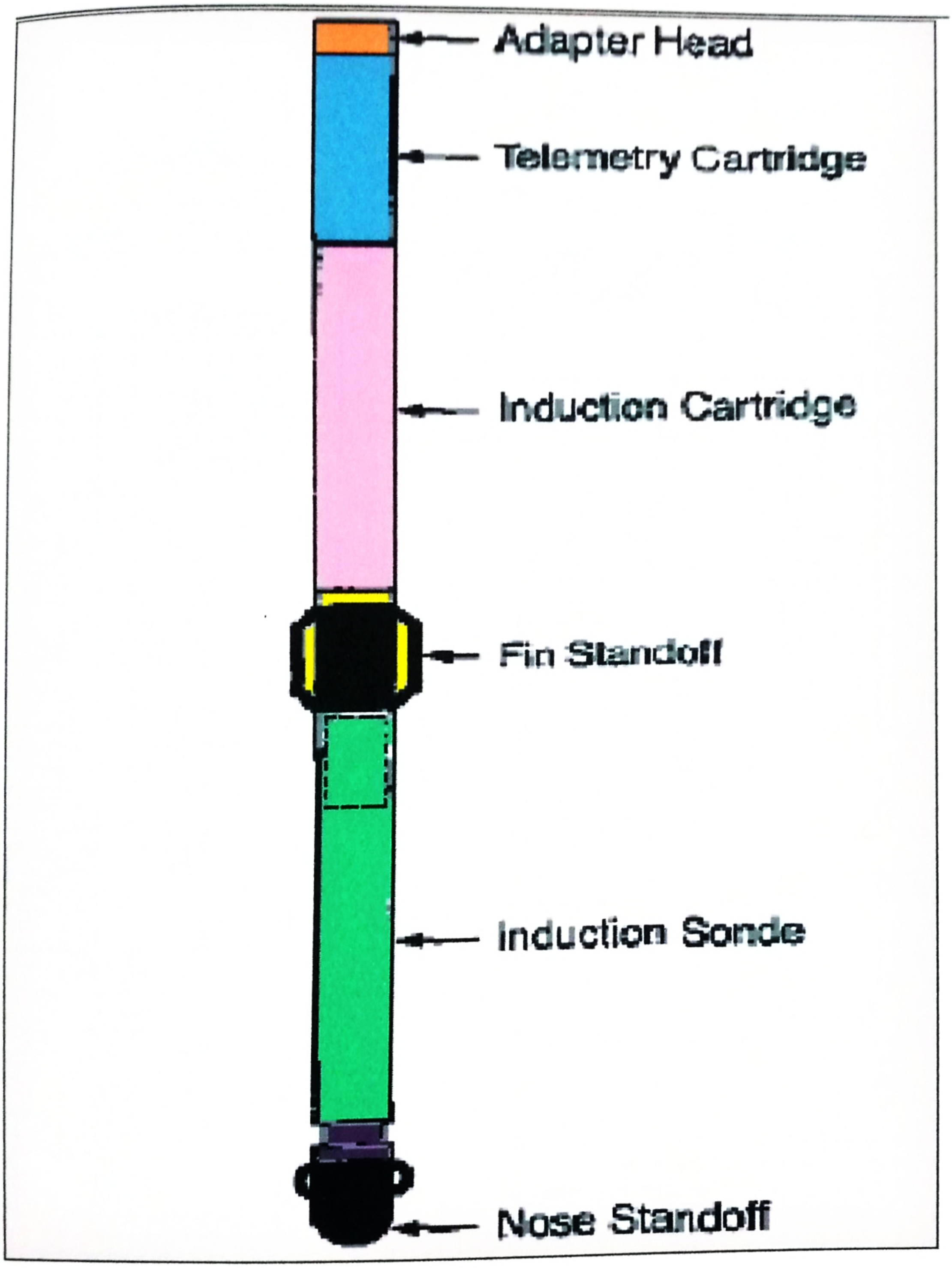

Figure 5.5: A schematic of the Phasor Induction-SFL tool.

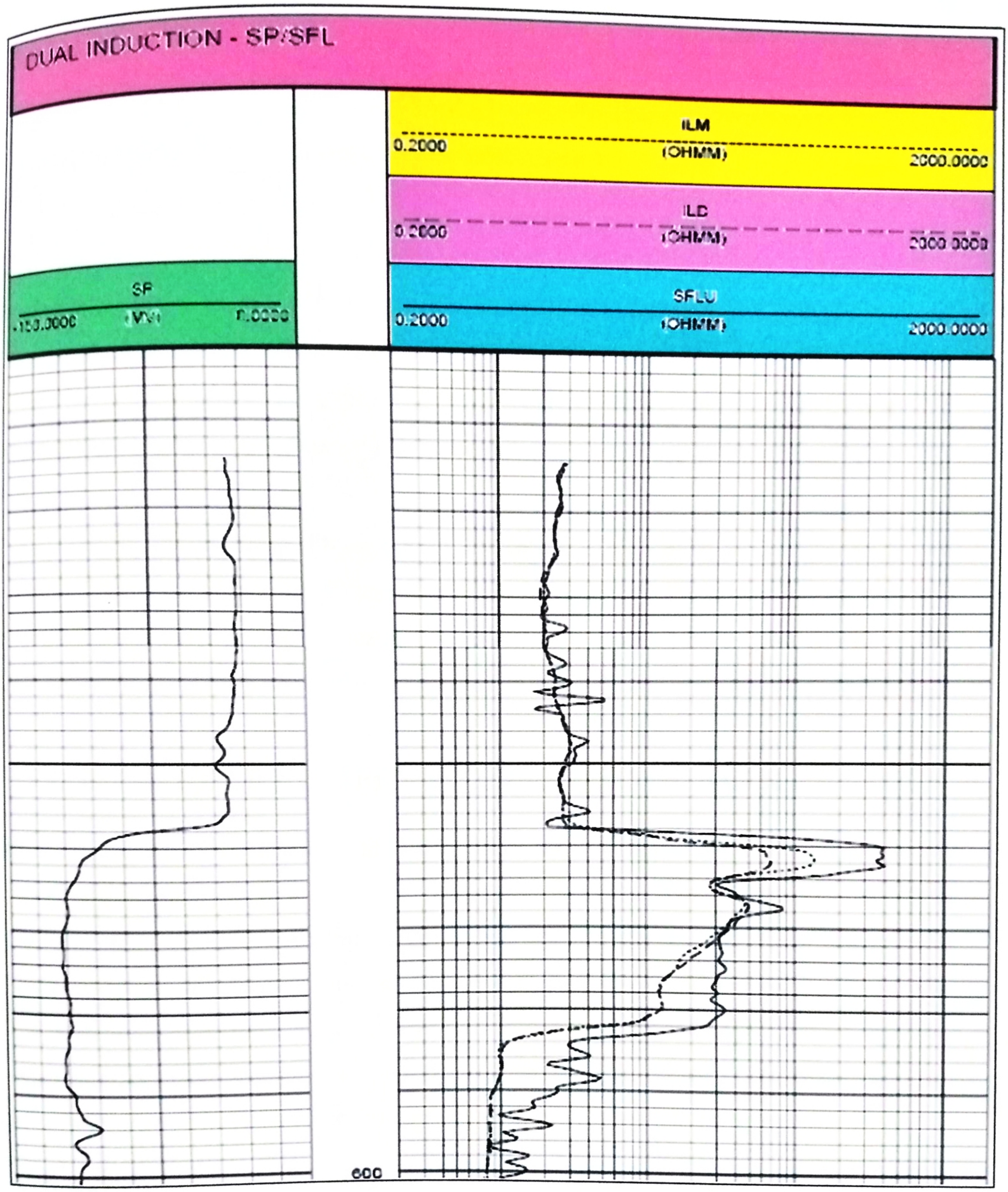

Figure 5.6: The three basic curves of ILD (ohmm), ILM (ohmm) and SFLU (ohmm) obtained from the dual induction tool (Schlumberger Drilling Services Catalog, 2001).

5.8.1 PRINCIPLE

In its simplest form, a sonic tool consists of a transmitter that emits a sound pulse and a receiver that picks up and records the pulse as it passes the receiver.

The sound emanated from the transmitter impinges on the borehole wall. This establishes compressional and shear waves within the formation, surface waves along the borehole wall and guided waves within the fluid column. The sonic log is simply a recording versus depth of the time, t_{comp}, required for a compressional sound wave to traverse 1 m of formation.known as the interval transit time.

The interval transit time for a given formation depends upon its lithology and porosity.This dependence upon porosity, when the lithology is known, makes the sonic log useful as a porosity log. Integrated sonic transit times are also helpful in interpreting seismic records.

5.8.2 BORE HOLE COMPENSAED (BHC) SONIC TOOL

Sonic tools in current use are of the BHC type (Figure 5.7). This type sonde substantially reduces spurious effects at hole size changes as well as errors due to sonde tilt. The `BHC' system uses transmitter above and one transmitter below two pairs of sonic receivers. When one of the transmitter is pulsed, the sound wave generated enters the formation; the time elapsed between detection of the first arrival at the two corresponding receivers is measured. The □*t* values from the two sets of receivers are averaged automatically by a computer at the surface for borehole compensation.

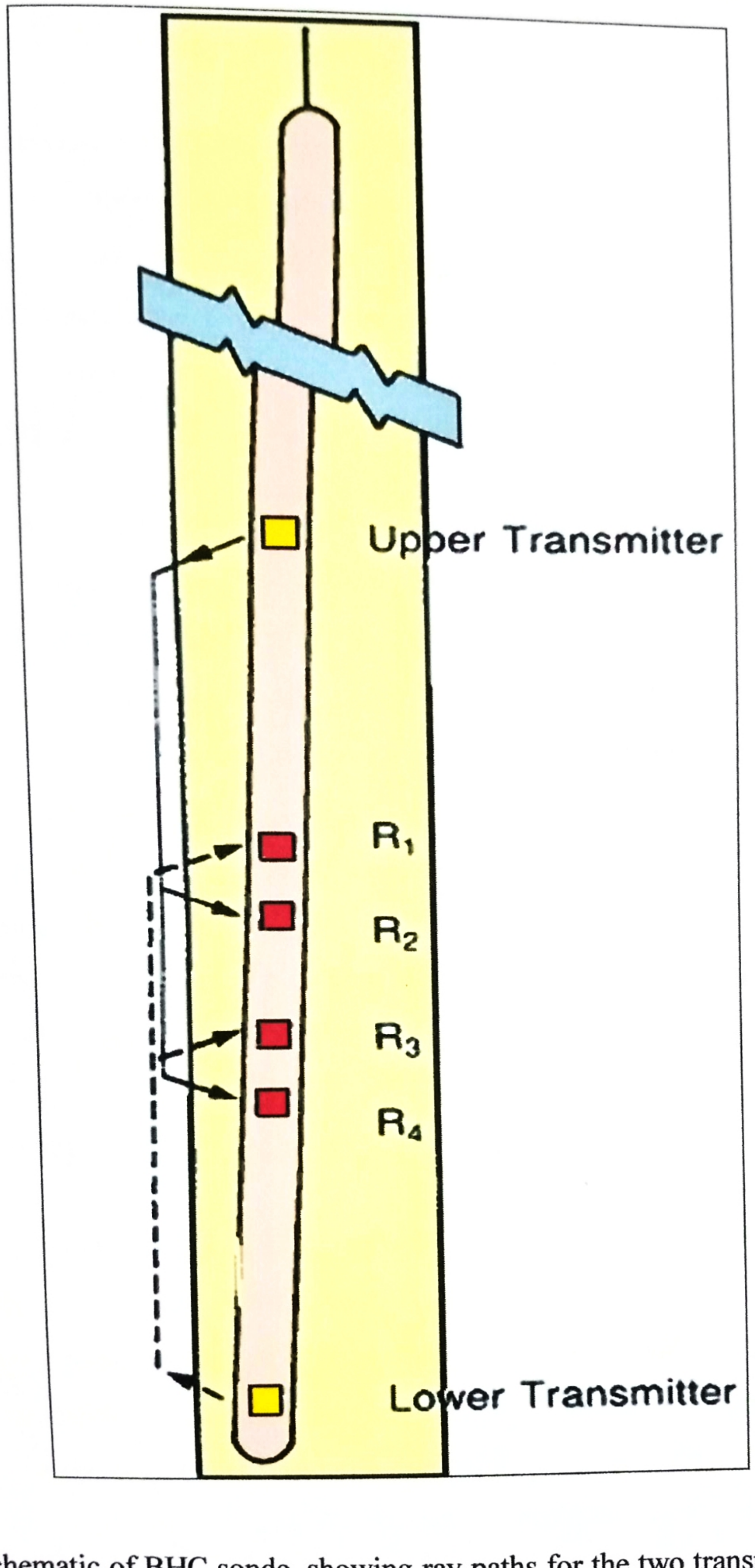

Figure 5.7: Schematic of BHC sonde, showing ray paths for the two transmitter-receiver sets. Averaging the two Dt measurements cancels errors from the sonde tilt and hole-size charges.

5.9 DENSITY LOG

Density logs are primarily used as porosity logs. Other uses include identification of minerals in evaporate deposits, detection of gas, determination of hydrocarbon density, evaluation of shaly sands and complex lithologies, determinations of oil-shale yield, calculation of overburden pressure and rock mechanical properties.

5.9.1 PRINCIPLE

A radioactive source, applied to the borehole wall in a shielded sidewall skid, emits medium-energy gamma rays into the formations. These gamma rays may be thought of as high velocity particles that collide with the electrons in the formation. At each collision a gamma ray loses some, but not all, of its energy to the electron, and then continues with diminished energy. This type of interaction is known as Compton scattering. The scattered gamma rays reaching the detector, at a fixed distance from the source, are counted as an indication of formation density. The number of Compton-scattering collisions is related directly to the number of electrons in the formation. Consequently, the response of the density tool is determined essentially by the electron density (number of electrons per cubic centimeter) of the formation.

5.9.2 COMPENSATED FORMATION DENSITY (FDC) TOOL

In the FDC tool, two detectors of differing spacing and depth of investigation are used (Figure 5.8). The bulk density curve is recorded in Tracks 2 and 3 with a linear density scale in grams per cubic centimeter. The primary calibration standards for the FDC tool are laboratory freshwater-filled limestone formations of high purity and known densities. The secondary (shop c&bration) standards are large aluminum and sulfur blocks into which the sonde is inserted. These blocks are of carefully designed geometry and composition, and their characteristics have been related to the limestone formations.

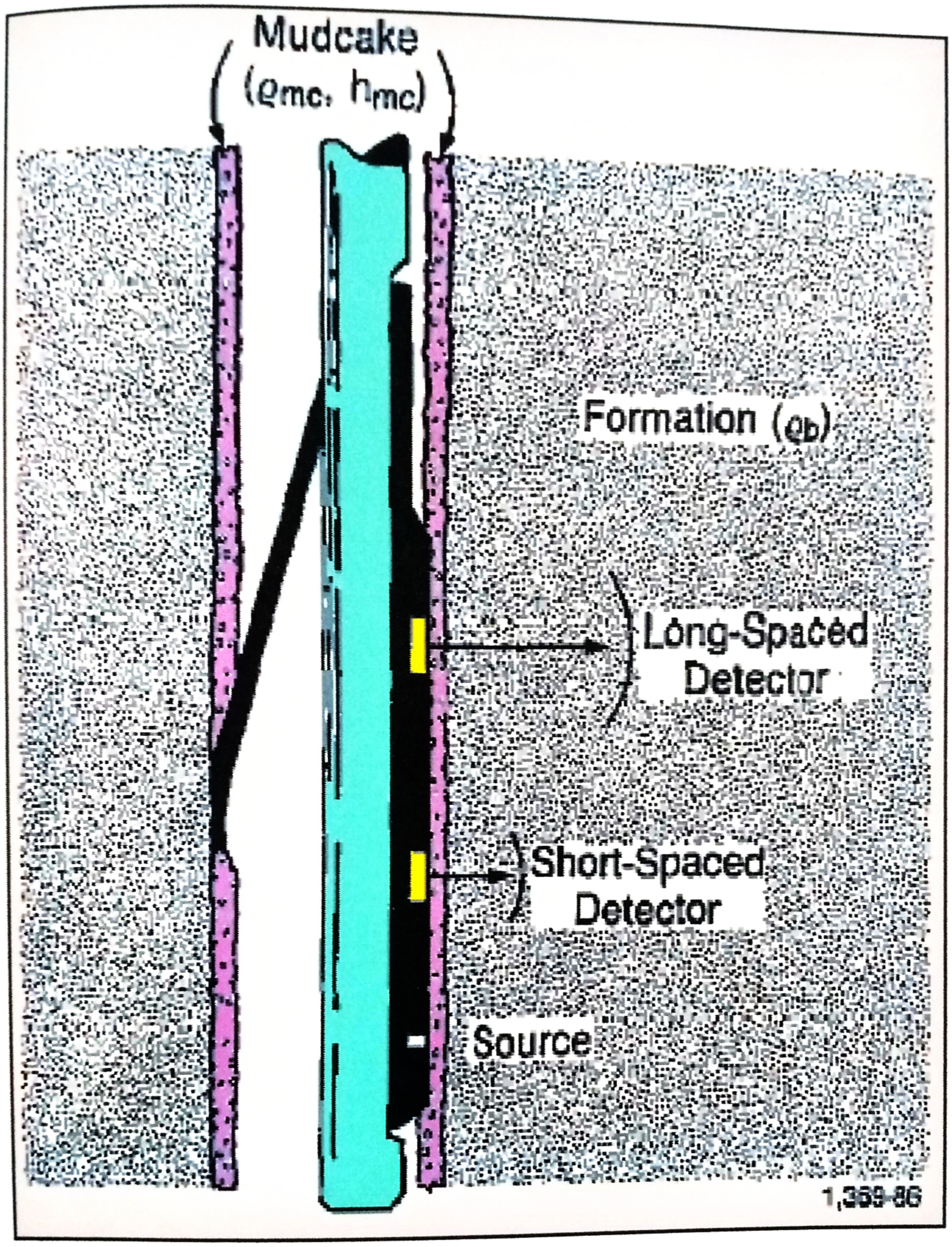

Figure 5.8: A schematic drawing of the Dual spacing formation density logging device. (Schlumberger Drilling Services Catalog, 2001).

5.10 NEUTRON LOG

Neutron logs are used principally for delineation of porous formations and determination of their porosity. It is basically a measure of the amount of hydrogen present in the formation. They respond primarily to the amount of hydrogen in the formation. Neutron logging tools include the SNP tool, the CNL tool (Figure 5.9).

5.10.1 PRINCIPLE

High energy neutrons are continually emitted from a radioactive source in the sonde. These neutrons collide with nuclei of the formation material. With each collision, the neutron loses some of its energy. The amount of energy lost per collision depends on the relative mass of the nucleus with which the neutron collides. Within a few microseconds, the neutrons have been slowed by successive collisions. These neutrons or the captured neutrons are counted by the detector in the sonde.

5.11 GAMMA RAY LOG

The gamma ray log measures the natural radioactivity response of the formations. The log is therefore useful to identify lithologies and for correlation purposes. Gamma rays are bursts of high-energy electromagnetic waves that are emitted spontaneously by some radioactive elements. Nearly all the gamma radiation encountered in the earth is emitted by the radioactive potassium isotope of atomic weight 40 (K^{40}) and by the radioactive elements of the uranium and thorium series.

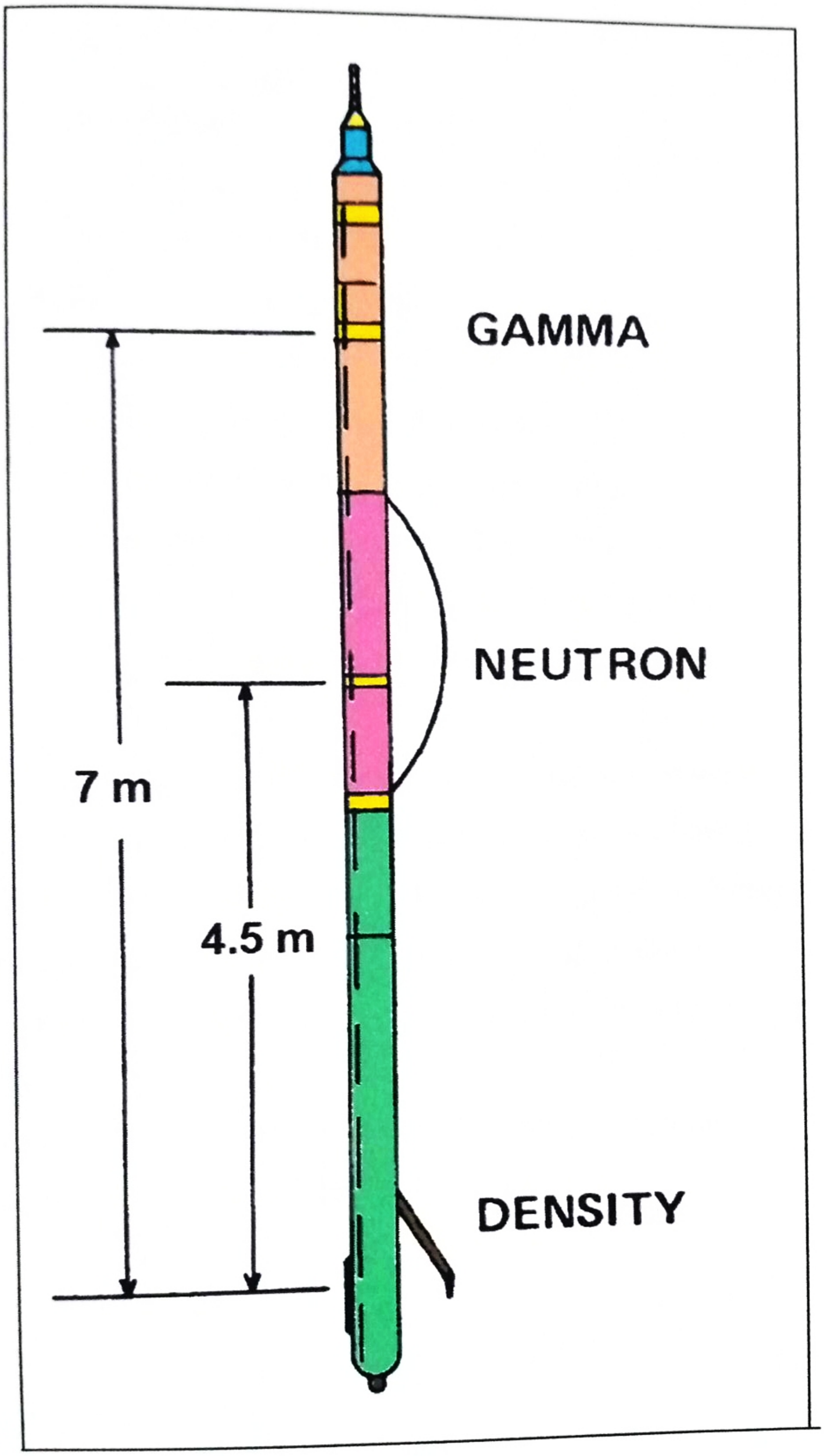

Figure 5.9: Basic SGT-CNL-LDT tool configuration

5.12 REPEAT FORMATION TESTER (RFT)

The repeat formation tester tool has been designed to :

1. Measure formation pressures
2. collect reservoir fluid samples

Depth accuracy can be controlled by correlating a gamma ray curve or an SP curve with the open hole logs. RFT device is capable of high precision pressure measurements, it can retrieve two fluid samples per trip in the hole. The tool can be set at any desired depth independent of mud pressure. Even at very shallow depths, it still has enough setting force to provide a good seal with the formation through the packer.

Two pretest chambers (Figure 5.10), automatically activated everytime the tool is set, withdraw 10 cc of formation fluid each. The repeat formation tester (RFT) is operated by an electrically driven hydraulic system so that it can be set and retracted as often as necessary to pressure test all zones of interest on one trip in the well. Two separate fluid tests can also be taken on one trip.

After dilling down to 1914m, RFT was carried out by Schlumberger at Bijnot Well No.01. The summary of the RFT is given in Table 5.1.

Table 5.1: Summary of RFT run in well X-1.

DEPTH	HYDROST BEFORE	PRESSURE AFTER	F. PRESSURE	REMARKS
M		PSIA	PSIA	
1898.2				DRY TEST
1896.9				DRY TEST
1875.8				DRY TEST
1887.5				DRY TEST
1861.5				DRY TEST
1851.0			2759.2	SEGREGATED SAMPLE
1850.9	3225.3	3228.2	2809.8	LOW PERM
1850.5	3219.1	3225.5		DRY TEST
1848.4				DRY TEST
1847.0				DRY TEST
1845.0				DRY TEST
1844.5	32.7.5	3317.0	2784	TIGHT
1831.0				LOST SEAL
1754.5				DRY TEST
1714.5	2988.9	2980.8	42.4	EXCELLENT PERM
1594.0	2779.2	2776.4	2443.1	FAIR PERM
1588.0	2767.2	2765.7	2428.5	EXCELLENT PERM
1884.2	2761.2	2758.0	2418.4	FAIR PERM
1850.3	2751.7	2751.3	2416.8	GOOD PERM
1576.2	2753.1	2748.2	2411.6	GOOD PERM
1538.0	2681.0	-	2265.9	LOW PERM
1534.8	2668.5	2665.3	2332.9	FAIR PERM
1533.2	2671.8	2655.3	2630.4	LOST SEAL
1533.1	2669.3	2668.9	22.1	DRY TEST

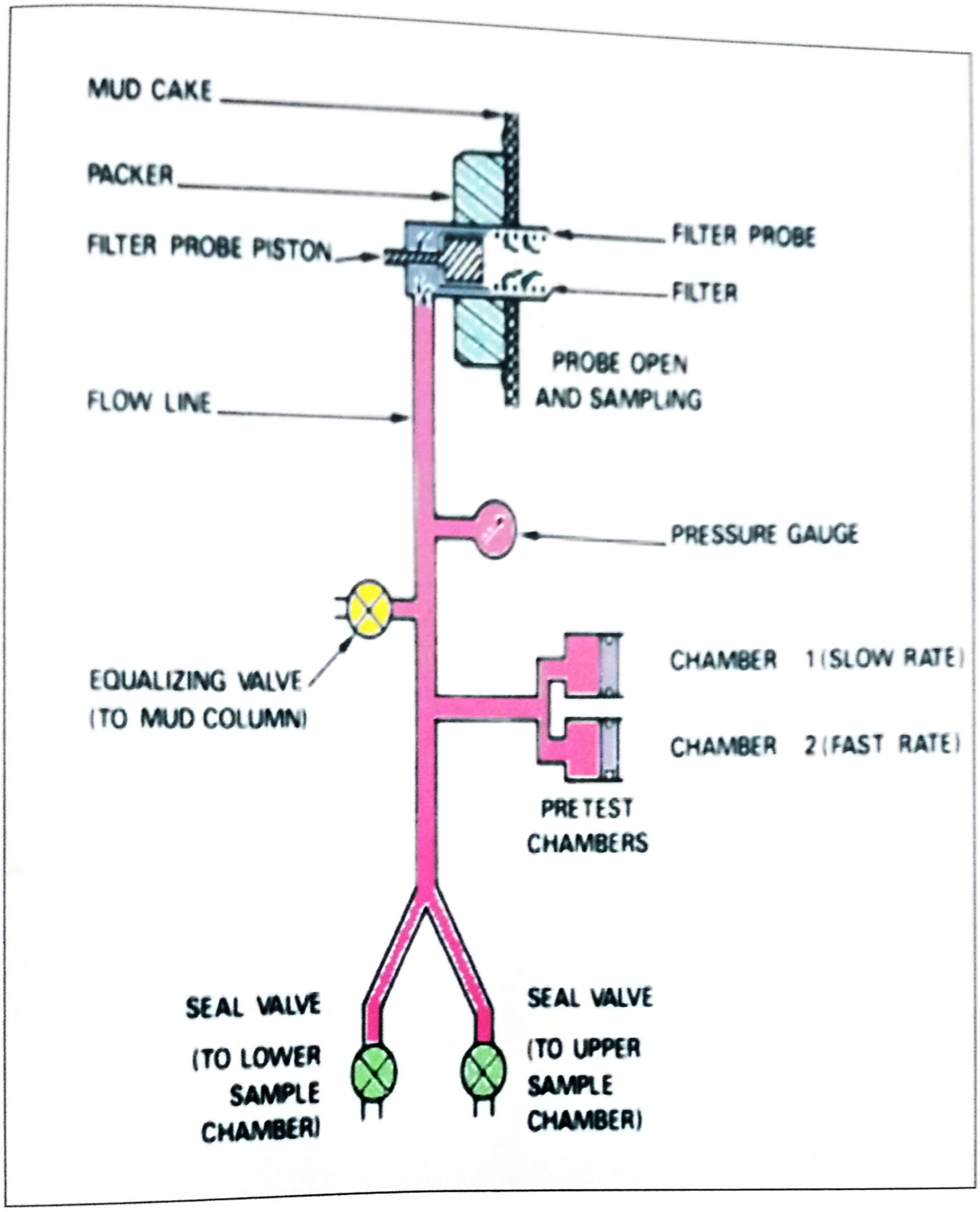

Figure 5.10: Basic RFT tool configuration (Schlumberger logging tools and principles, 2000).

CHAPTER 6

CORING

6. CORING

Two conventional and one set of side wall core (thirty samples at different depths) were cut at well X-1. The details are give bellow:

6.1 CONVENTIONAL CORES

6.1.1 CORE NO. 1

Date	13-08-96
Interval	1535 m to 1544 m
Recovery	0.25 m i.e., 2.77%
Coring Time	06.0hrs
Formation	Khewra
Age	Cambrian

Lithological Description And Remarks

Break Down (1535.00m-1535.10m)

Rock Type: Sandstone

It is white, whitish grey, grayish white, translucent, very hard, fine to medium grained, sub-rounded, moderately sorted, grains tightly packed within argillaceous matrix, micaceous, patches of pyrite embedded, at places bituminous and non calcareous.

Visual Porosity		3-4 %
Fluorescence	**Direct**	Nil
	Indirect	Nil
Gas recorded		Nil

Break Down (1535.10m-1535.25m)

Rock Type: Shale

It is greenish grey, grey, hard, dull, highly micaceous, pyritic, non calcareous. Laminations of brown siltstone are also present.

Fluorescences	**Direct**	Nil
	Indirect	Nil
Gas recorded		Nil

6.1.2 CORE NO.2

Date	27-08-96
Interval	1846 m to 1851 m
Recovery	3.39 m i.e., 67.8%
Coring Time	04.3 hrs
Formation	Salt Range
Age	Pre Cambrian

Lighological Description And Remarks

Break Down (1846.00m-1846.50m)

Rock Type: Claystone

It is reddish brown, moderately hard, sandy, quartz grains are embedded in rock matrix, occasionally gypsyferous and non calcareous

Dip		4^{o} approximately
Fluorescences	**Direct**	Nil
	Indirect	Nil
Gas recorded		Nil

Break Down (1846.50m-1847.25m)

Rock Type: Silstone

It is reddish brown, brown, hard, highly arenaceous, grading into sandstone and non calcareous

Dip		4° approximately
Fluorescences	**Direct**	Nil
	Indirect	Nil
Gas recorded		Nil

Break Down (1847.25 m – 1848.20 m)

Rock Type: Sandstone

It is grey, dark grey, hard, fine to coarse grained, angular to sub-rounded, poorly sorted, cemented with calcitic and anhydritic material. Argillaceous laminations with regular interval.

Porosity		5-10%
Dip		4° approximately
Fluorescences	**Direct**	Poor
	Indirect	Fair
Gas recorded		Nil

Break Down (1848.20 m – 1848.55 m)

Rocky Type: Sandstone

It is grey in colour, crystalline, hard, vitreous and vugy.

Dip		4^{o} approximately
Fluorescences	**Direct**	Nil
	Indirect	Nil
Gas recorded		Nil

Break Down (1848.55 m – 1849.39 m)

Rocky Type: Sandstone

It is mainly grey in colour, hard to very hard, fine to medium grained, occasionally coarse grained, sub-angular to sub-rounded, poorly sorted, thin laminae of shale and claystone are present. It is cemented with anhydrite and argillaceous material.

Porosity		5-10%
Dip		4^{o} approximately
Fluorescences	**Direct**	Light brown, orange, un-even And weak
	Indirect	Golden yellow
Gas recorded		Nil

6.2 SIDE WALL CORING

Side wall coring was carried out by Schlumberger against interval of 1758 -1533 m at 30 different points. Out of which seventeen samples were recovered. Five were full of mud cake and eight were empty. No hydrocarbon shows were observed except in sample of 1725 m. In direct Ultraviolet light, it gave weak light brown fluorescence and black uneven asphaltic stain. During cut, it gave fair to good golden yellow fluorescence.

CHAPTER 7

METHODOLOGY

7. INTERPRETATION WORK FLOW

The parameters are calculated for the saturation of hydrocarbons according to work flow. The complete interpretation work flow is shown in Figure 7.1.

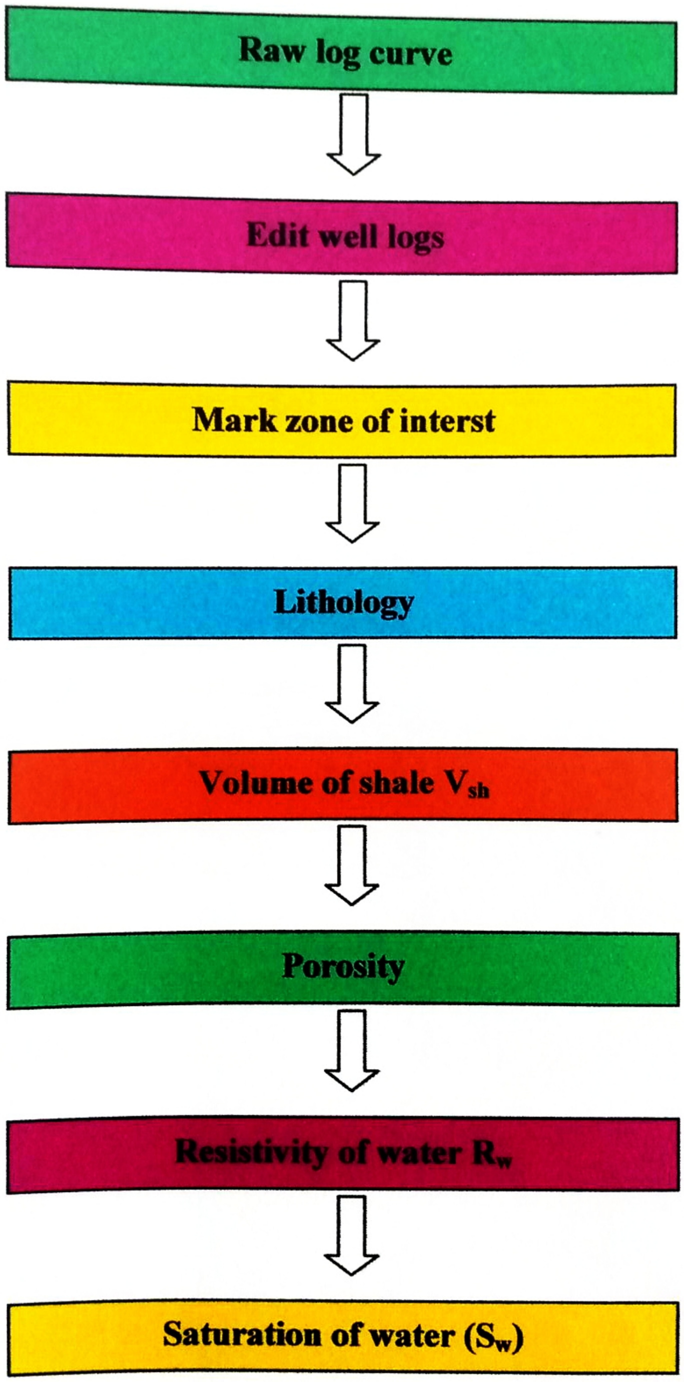

Figure 7.1: A complete interpretation workflow used for calculating hydrocarbon saturation.

7.1 ARCHIE'S EQUATION

In general terms the petrophysical techniques that are used to study the parameters a, m, n and R. The techniques all use the relationships defined by the Archie equation:

$$S_W^N = \frac{a}{\Phi n} \times \frac{Rw}{Rt}$$

$$= F \times \frac{Rw}{Rt}$$

$$= \frac{Ro}{Rt}$$

where:

where:	S_w	is the water saturation
	R_t	is the deep resistively
	R_w	is the resistivity of the formation water
	n	is the saturation exponent
	m	is the cementation exponent
	a	is the tortuosity factor
	F	is the formation resistivity factor
	R_0	is the wet resistivity

7.2 PICKETT PLOTS

A Pickett plot is a crossplot of porosity versus resistivity on log-log graph paper. This represents a rearrangement of the Archie equation into the following form:

$$\mathbf{Log\ R_t = -m\ log\,\Phi + log\ (aR_w) - n\ log\ S_w}$$

When log data is plotted on such a plot the "wet" points ($S_w = 1$) define a line with a slope equal to "-m" and an intercept equal to the product "aR_W".

The way in which Pickett plots can be used depends on which of the parameters "a", "m", "n", R_w and S,, are known. A typical procedure is to assume that S_w is known to be 1.0 for some plotted points. A line drawn through these points results in values for "m" and "aR_w". If R_w is known then "a" can be calculated. Now, with values for "m", "a" and R_w, and using an assumed value for "n", lines can be drawn on the plot for varying values of S_w. With these new lines the plot assigns water saturation values to each of the plotted log points. An example of an alternative application of Pickett plots is in determining R_w when "m" and "a" are known and some plotted points are "wet" points.

7.3 DETERMINATION OF “m” FROM CORE

The cementation factor “m” can be determined from the results of special core analysis. Core samples of varying porosity are saturated with a brine of known resistivity. The resistivity of each saturated sample is measured. In this situation S_w is known to be 1.0 and "a" is typically assumed to be 1.0.

Archie's equation reduces to:

$$\mathbf{Log}\ \frac{Rt}{Rw} = \mathbf{-m\ log\ \Phi}$$

A plot on log-log paper of the ratio of the core resistivity to the brine resistivity versus the porosity of each core sample defines a line with a slope equal to "-m". This technique is usually repeated with the core sample subjected to successive simulated overburden pressures to detect any mechanical changes that may be attributed to the applied pressure. Studies have shown that "m" is related to the degree of cementation, and to changes in applied pressure. In some areas "m" is referred to by the name "lithology" exponent.

7.4 DETERMINATION OF "n" FROM CORE

The saturation exponent is also derived from special core analysis. A dry core sample is weighed. It is then saturated with brine and its resistivity (R_0) is measured. Through the use of a semi-permeable membrane and/or a centrifuge the sample is gradually desaturated. At different stages during the desaturation the sample is weighed to determine the brine remaining in the core. This is converted to a water saturation using the previously measured core porosity. The resistivity (R_t) is also measured at the time of each weighing. The resistivity is usually expressed as the resistivity index R_t/R_O. This situation is described by Archie's equation in the following form.

$$\log \frac{Rt}{Ro} = -n \log S_w$$

A plot of resistivity index versus brine saturation on log-log paper defines a line with a slope of "-n".

7.5 SHALE VOLUME

The shale volume was determined as part of the Petrophysical analysis of the reservoir. The shale volume can be determined using the Neutron Porosity and the Gamma ray.

The volumes of shale were estimated from Gamma Ray. The shale volume was taken as the minimum of the volumes calculated by the two methods. Where it was available CGR from NGT was substituted for GR in calculating Gamma Ray shale volume. For all zones the shale volume was calculated using the following formula:

$$V_{SHgr} = \text{Shale volume from gamma ray log} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

7.6 POROSITY

The porosity for most of the sections of this well has been computed from Neutron-Density crossplot (Figure 7.2). The values of Neutron are first read from the neutron log. Similarly, the values for density log are also read from the density log. In wash out zones porosities have been computed from BHC. In case when sonic log is used with neutron log for finding porosity, use a sonic-neutron porosity crossplot (Figure 7.3).

7.7 DETERMINATION OF R_w

The Rw can be determined by using the following methods:

1. From SP log
2. From resistivity logs
3. From produced water

7.7.1 Rw FROM SP LOG

Because of its dependence on R_{mf} and R_w, the magnitude of SP deflection enables us to solve for the R_w of the formation when R_{mf} is known. This method, when applied in clean matrix, is generally accurate.

1. From the log header, get R_{mf} at BHT (borehole temperature).
2. Now, at a measured temperature of 76 °F, check value of Rmf from log header.
3. Calculated R_{mf} equivalent by using chart given in Figure 7.4
4. Calculate static SP (or SSP) from SP log.
5. Calculated R_{weq} by using chart given in Figure 7.5.
6. Calculated R_W @ BHT by using graph in Figure 7.6.

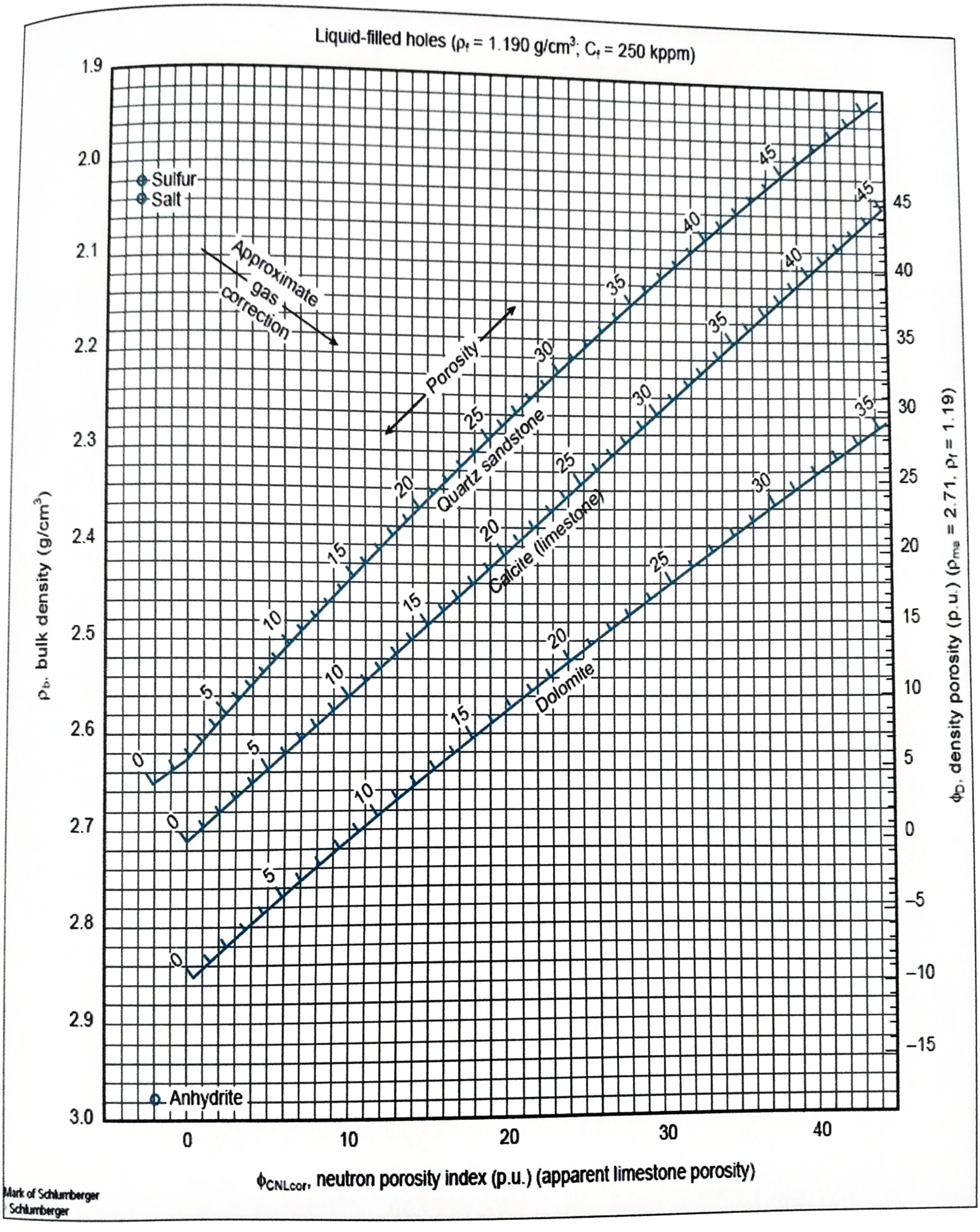

Figure 7.2: Crossplot used for finding porosity form Litho-density log and Compensated neutron log (Schlumberger chart book, 2000).

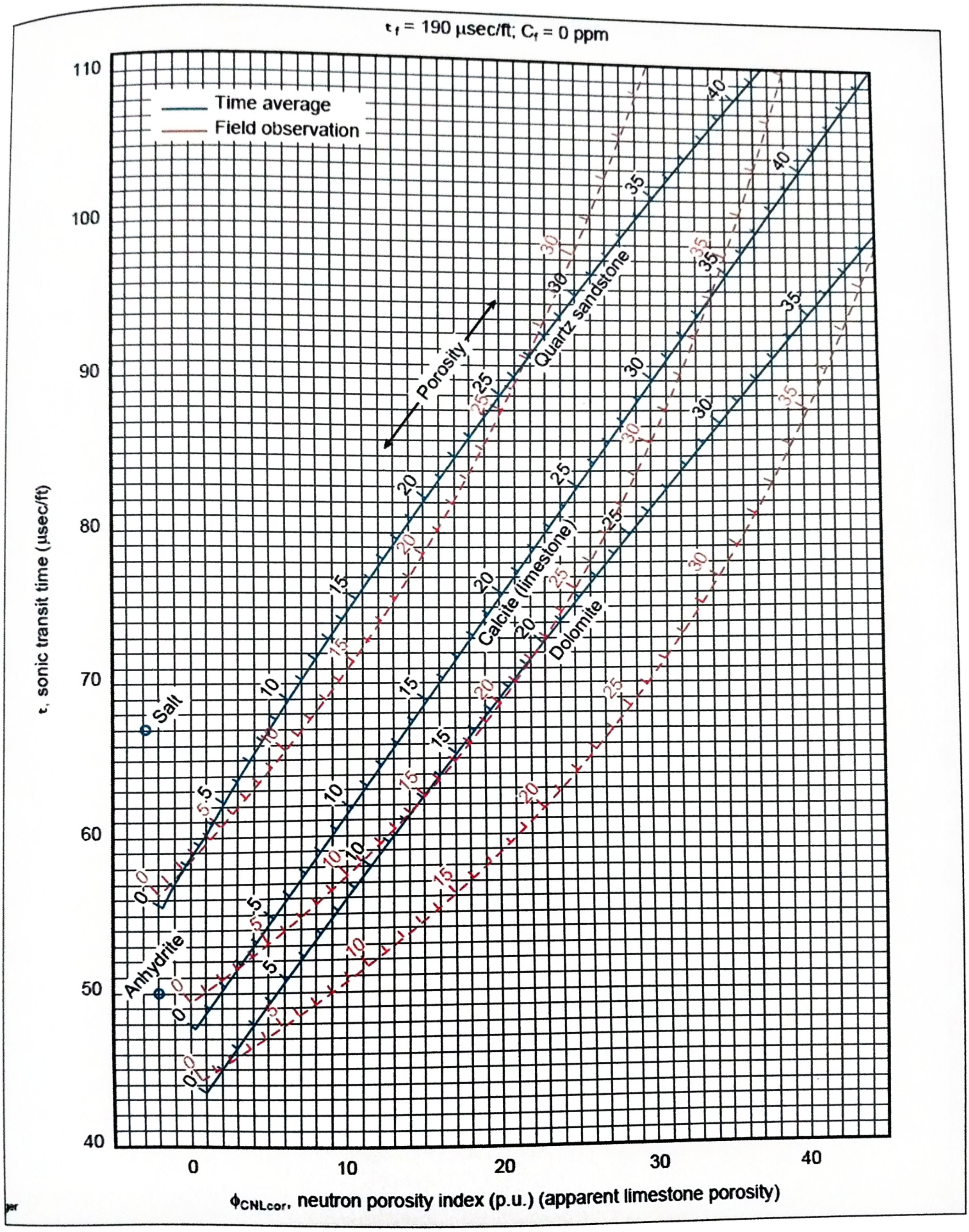

Figure 7.3: Crossplot used for finding porosity form Sonic log and Compensated neutron log (Schlumberger chart book, 2000).

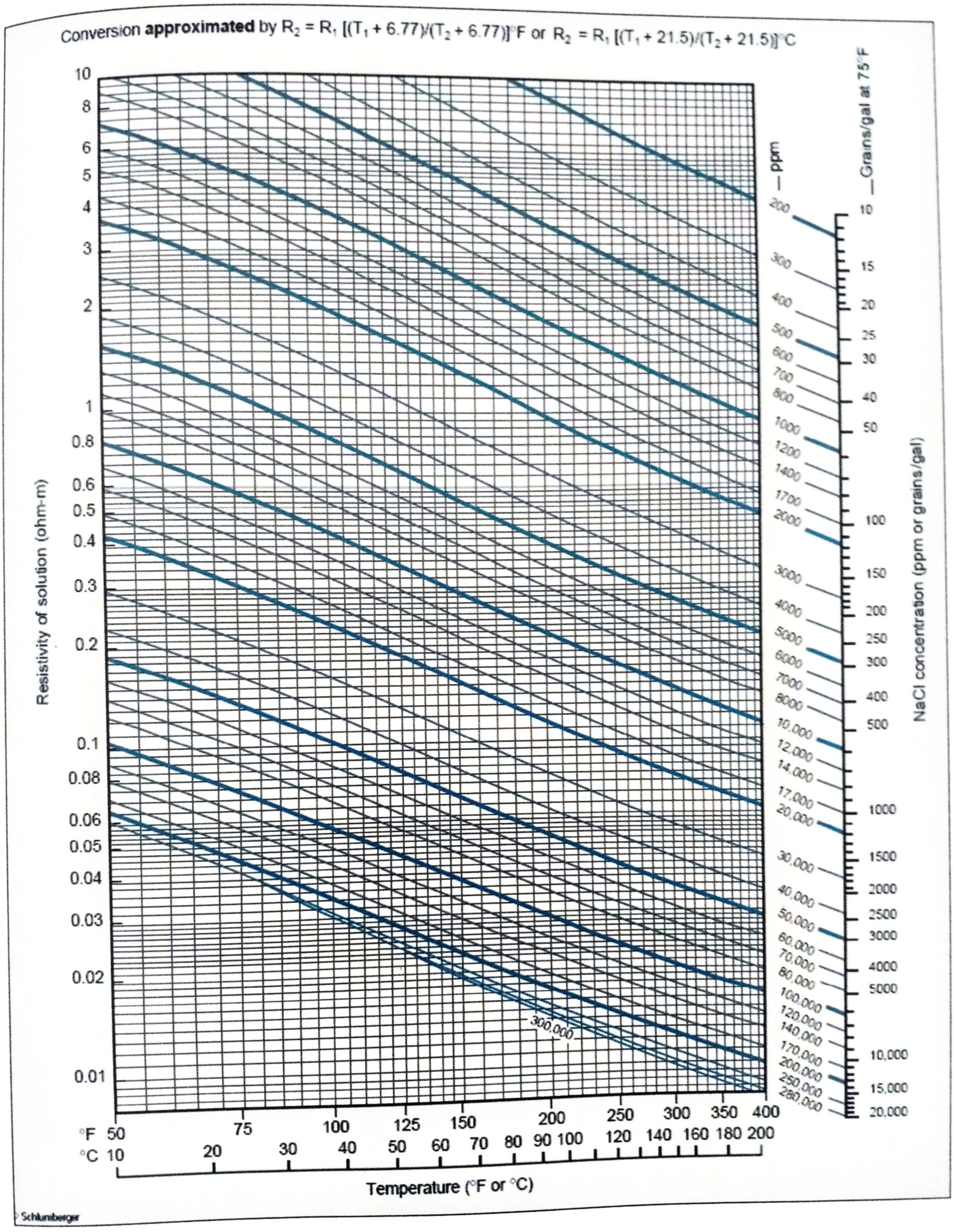

Figure 7.4: Chart used for the calculation of R_{mf} equivalent (Schlumberger chart book, 2000).

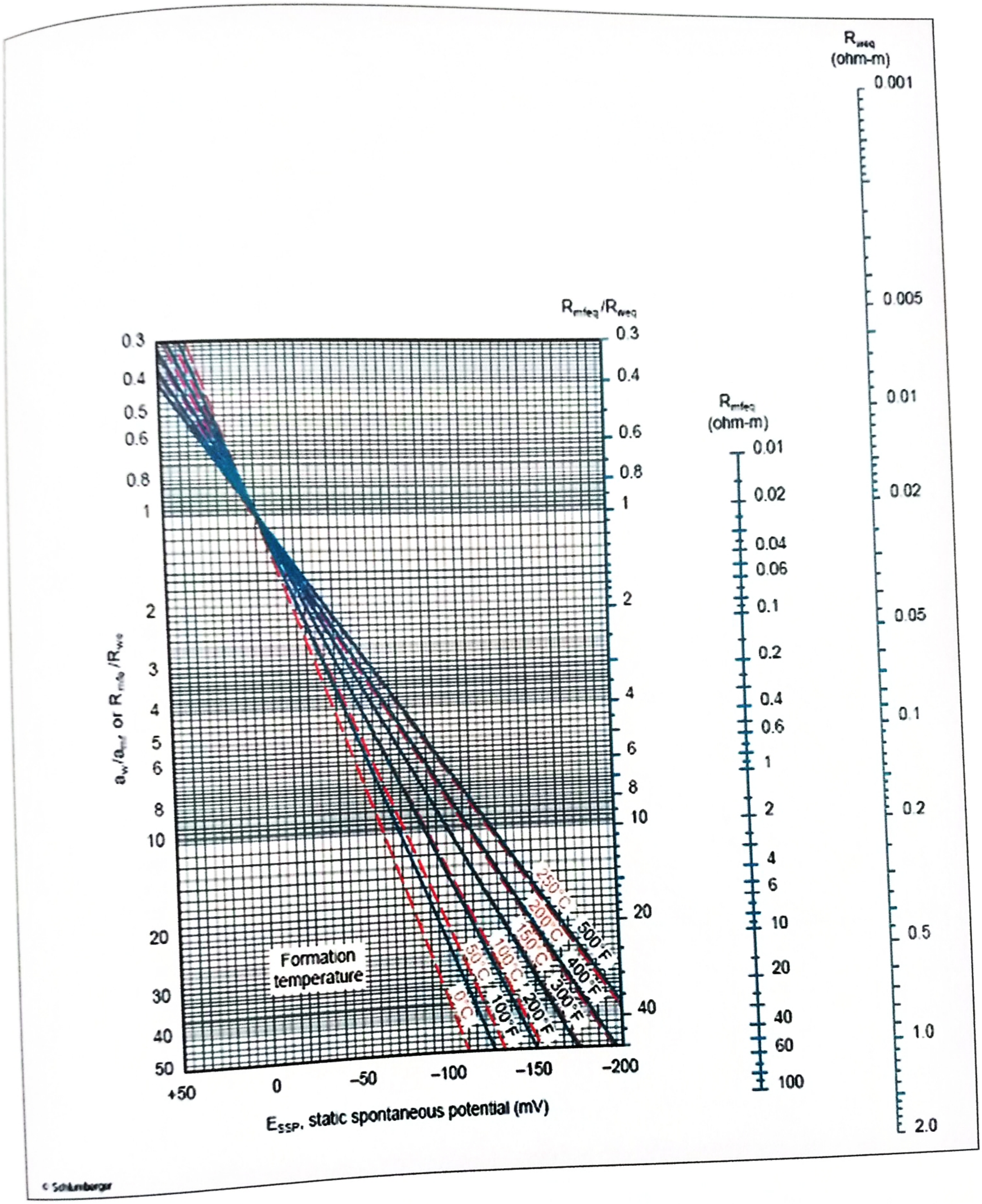

Figure 7.5: Chart used to calculate the equivalent formation water resistivity, Rweq, from the static spontaneous potential, E_{SSP}, measurement in clean formations (Schlumberger chart book, 2000).

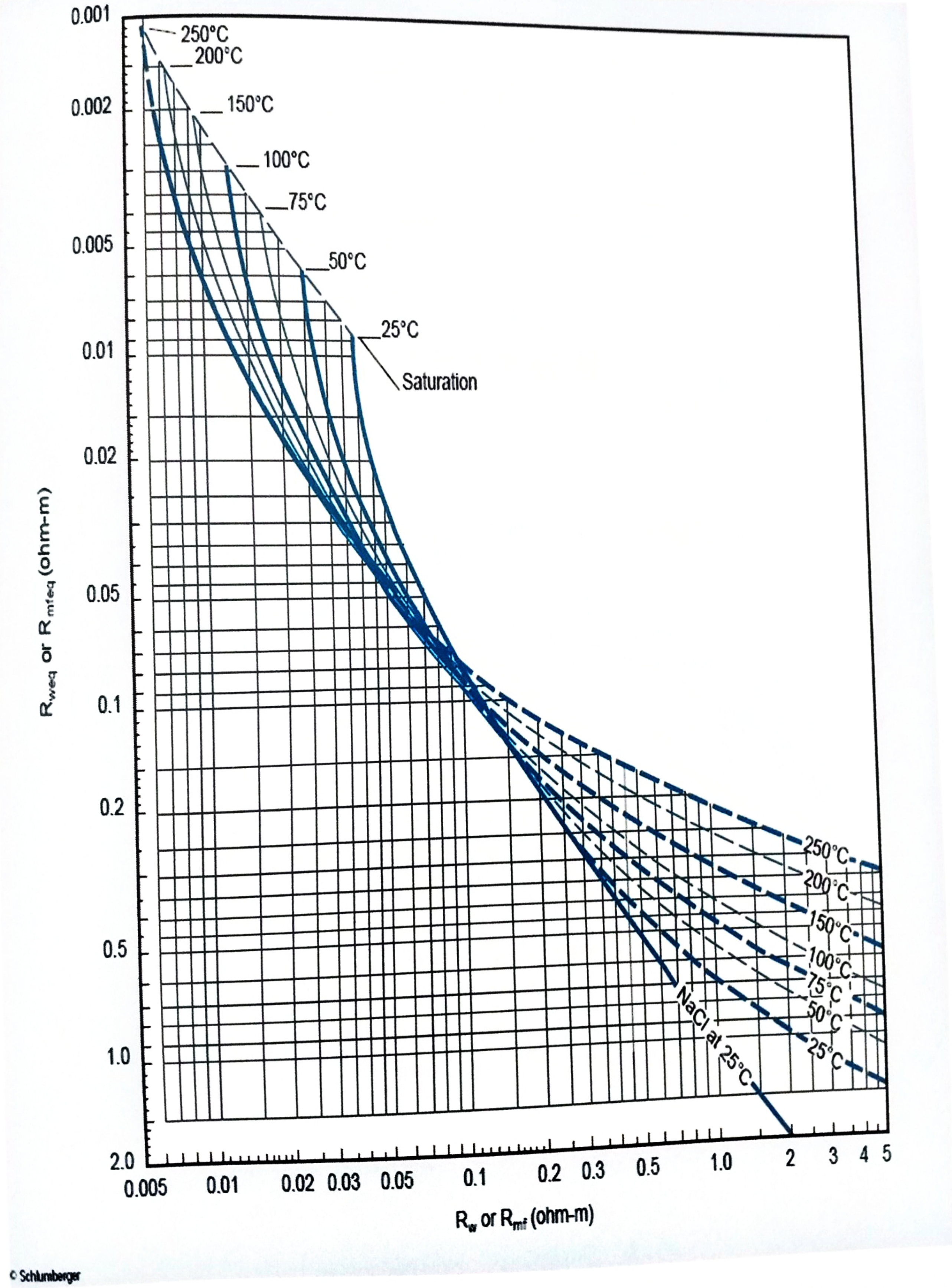

Figure 7.6: Chart used in finding Rw @ BHT (Schlumberger chart book, 2000).

CHAPTER 8

INTERPRETATION

8.1 ZONE # 1 (1532-1535 m)

The various zones that were marked for interpretation are shown in log of Enclosure # 1.

8.1.1 SHALE VOLUME

GR_{max} = 210 (GAPI) @ Depth=1539 m

GR_{min}=15 (GAPI) @ Depth=1729 m

GR_{log}= 33 (API) @ Depth=1533 m

Shale Volume= **Vsh**= $\frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$

$$= \frac{33 - 15}{210 - 15}$$

$$= .092$$

$$= 9.2\%$$

Similarly, the shale volume calculated at Depth= 1534 m came out to be

$$\mathbf{Vsh} = \frac{45 - 15}{210 - 15}$$

$$= 0.15$$

$$= 15\%$$

8.1.2 POROSITY

Bulk density Value= RHOB= 2.8 (G/C3) @ 1533 m

NPHI= 10 (V/V) @ 1533 m

From Density-Neutron crossplot,

Porosity= Φ = 6.5%

Transit time DT= 75 (US/F) @ 1534 m

NPHI=16 (V/V) @ 1534 m

From Sonic-Neutron crossplot,

Porosity= Φ =18 %

8.1.3 CALCULATION OF R_w

R_{mf} @ BHT (142 °F) = 0.022 ohm-m.

R_{mf} @ 76 °F = 0.041 ohm-m.

SSP = Static Spontaneous Potential = -15 mV

R_w = 0.03 ohm-m @BHT

8.1.4 WATER SATURAION (S_w)

For calculating S_w, Archie's equation for calculation of water saturation in a formation has been used.

$$S_w = \sqrt{1/\Phi^2 \times R_w/R_t}$$

For Zone 1, at depth=1533 m,

S_w = 0.7 = 70%

8.1.5 HYDROCARBON SATURATION

Hydrocabon Saturation=S_h= 1-S_w

= 1- 0.7

= 0.3

So, in the given zonen, S_h= 30%.

8.1.6 RESISTIVITY OF TRUE OR UNINVADED ZONE

For R_t , read the value of LLD (Laterolog deep) at the respective zone. In the Zone 1, the value of R_t= 17 (ohmm).

The graph plotted between Sw at the corresponding depth of zone 1 is shown in Figure 8.1.

8.1.7 RESULT

So, from the above parameters, we can say that this zone is water wet, as the S_w has come out to be high, upto 70%. In this zone the shale volume is considerably low but the RFT at depth of 1533.1 m showed a dry test result. Further at 1534.3 m depth, the RFT showed a fair permeability as at this depth shale volume was also quite low.

8.2 ZONE # 2 (1537-1538.5 m)

For zone 2, the computation of shale volume is given in Table 8.1 and the evaluation of porosity, Rt, S_w and S_h is given in Table 8.2.

Table 8.1: Basic shale volume evaluation by using gamma ray log.

DEPTH (m)	GR_{max} (GAPI)	GR_{min} (GAPI)	GR_{log} (GAPI)	V_{sh} (%)
1537	210	15	105	46.1
1538	210	15	91	38

In the given zone shale volume lies in the range of 38-46%. This shale content is higher than the zone 1. The graph plotted between Sw at the corresponding depth for this zone is shown in Figure 8.2

Table 8.2: Porosity, S_w and S_h calculations.

DEPTH (m)	DT (US/F)	NPHI (V/V)	Rt (ohmm)	POROSITY (%)	S_w (%)	S_h (%)
1537	77	19	2	20	61.2	38.7
1538	77	16	1.5	18	78.56	21.4

In this zone, porosity has been calculated by using the sonic-neutron crossplot, because the RHOB response was not very accurate.

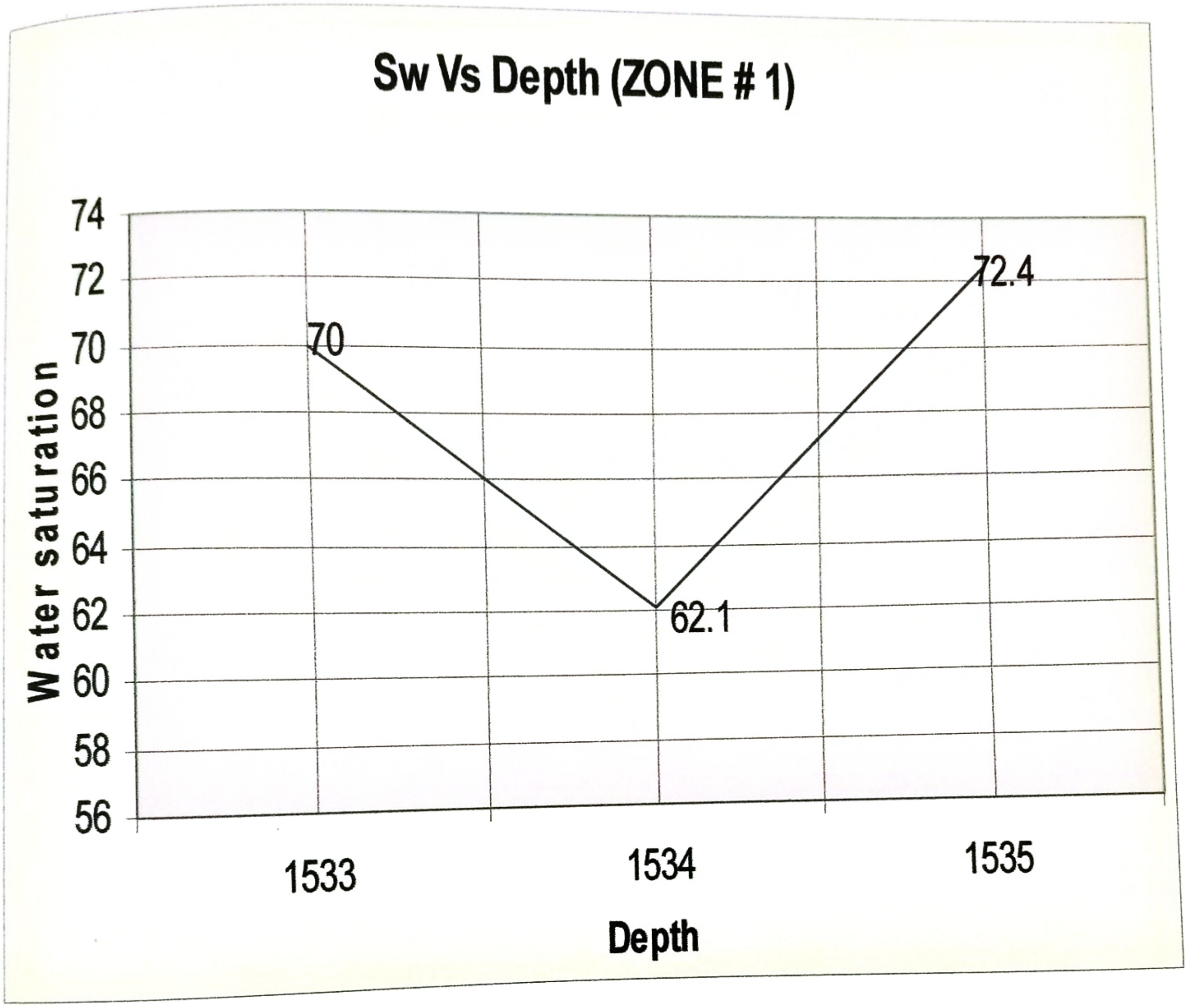

Figure 8.1: A graph between Sw and depth for Zone 1.

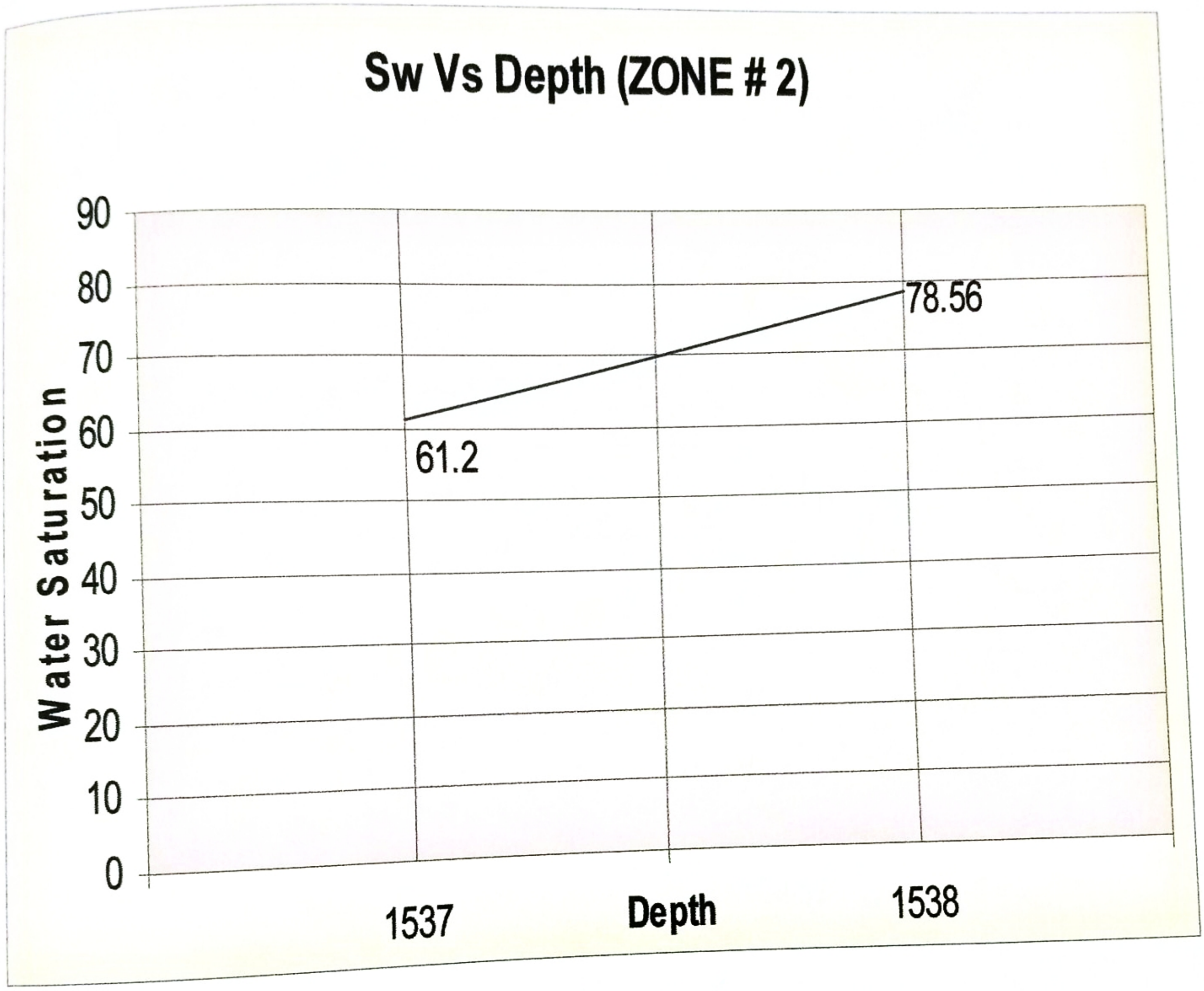

Figure 8.2: A graph between Sw and depth for Zone 2.

8.2.1 RESULT

This zone is highly saturated with water or is water wet. In this range the shale content is quite high which resulted in low permeability.

8.3 ZONE # 3 (1548-1550 m)

For zone 3, the computation of shale volume is given in Table 8.3 and the evaluation of porosity, Rt, S_w and S_h is given in Table 8.4. The graph plotted between Sw at the corresponding depth of zone 3 is shown in Figure 8.3.

Table 8.3: Basic shale volume evaluation of Zone 3 by using gamma ray log.

DEPTH (m)	GR_{max} (GAPI)	GR_{min} (GAPI)	GR_{log} (GAPI)	V_{sh} (%)
1548	210	15	90	38.4
1549	210	15	105	46.1
1550	210	15	55	2.05

Table 8.4: Porosity, S_w and S_h calculations.

DEPTH (m)	RHOB (G/C3)	NPHI (V/V)	Rt (ohmm)	POROSITY (%)	S_w (%)	S_h (%)
1548	2.75	19	14	12.5	37	62.9
1549	2.88	2.5	50	1	77.45	22.5

8.3.1 RESULT

The given zone is also waterwet. The porosity of this zone is also not very high.

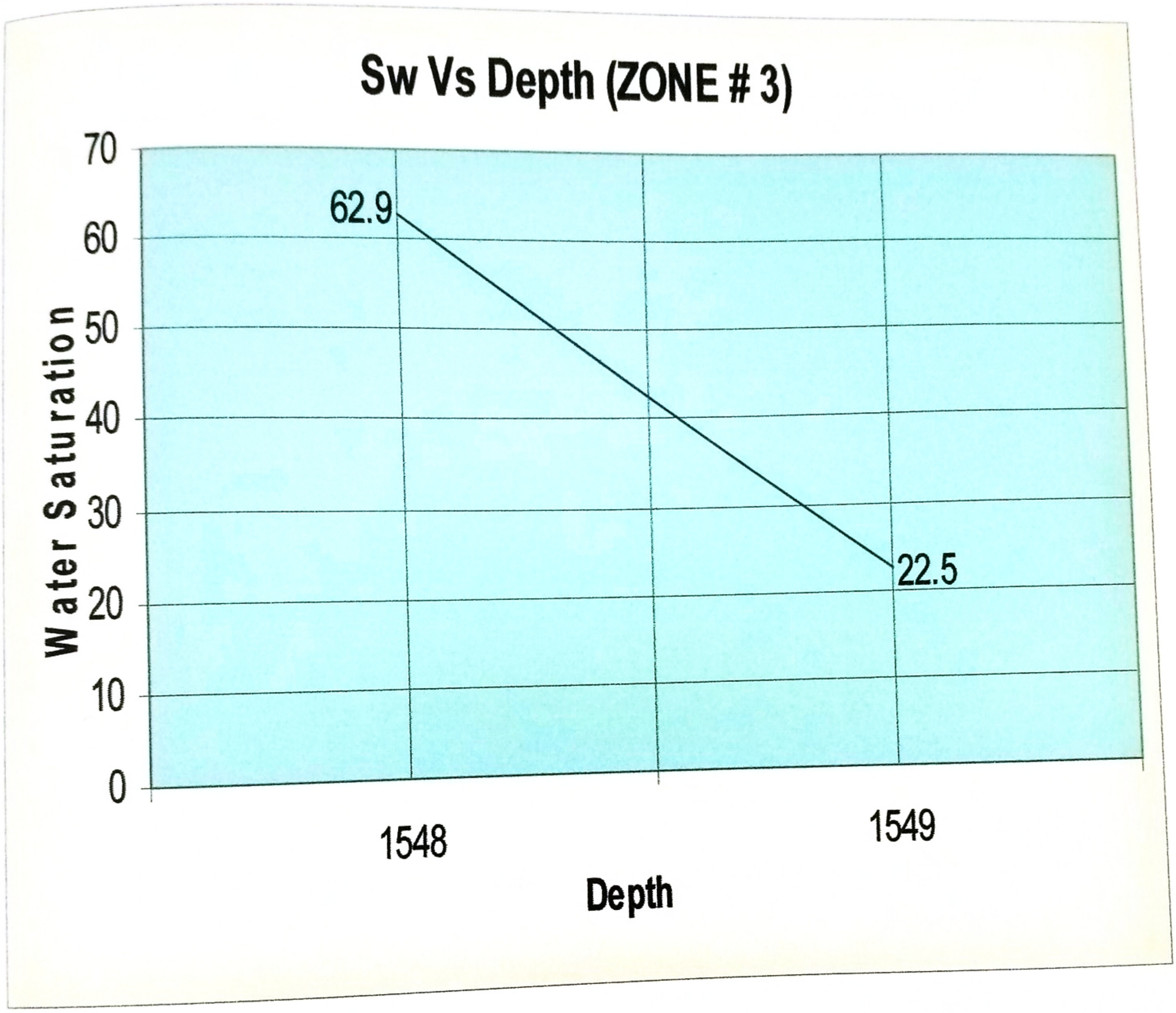

Figure 8.3: A graph between Sw and depth for Zone 3.

8.4 ZONE # 4 (1601-1609 m)

For zone 4, the computation of shale volume is given in Table 8.5 and the evaluation of porosity, Rt, S_w and S_h is given in Table 8.6. The graph plotted between Sw at the corresponding depth of zone 34 is shown in Figure 8.4.

Table 8.5: Basic shale volume evaluation of Zone 3 by using gamma ray log.

DEPTH (m)	GR_{max} (GAPI)	GR_{min} (GAPI)	GR_{log} (GAPI)	V_{sh} (%)
1601	210	15	133	60.5
1602	210	15	120	53.8
1603	210	15	114	50.7
1605	210	15	105	46.1
1606	210	15	90	38.4
1607	210	15	120	53.8

Table 8.6: Porosity, S_w and S_h calculations.

DEPTH (m)	DT (US/F)	NPHI (V/V)	Rt (ohmm)	POROSITY (%)	S_w (%)	S_h (%)
1601	78	20	1.5	18	78.5	21.5
1602	80	24	0.9	23	79.2	20.2

8.4.1 RESULT

In the given zone, both the volume of shale and S_w are quite high. Although porosity is good, but the permeability will be highly affected by shale volume factor.

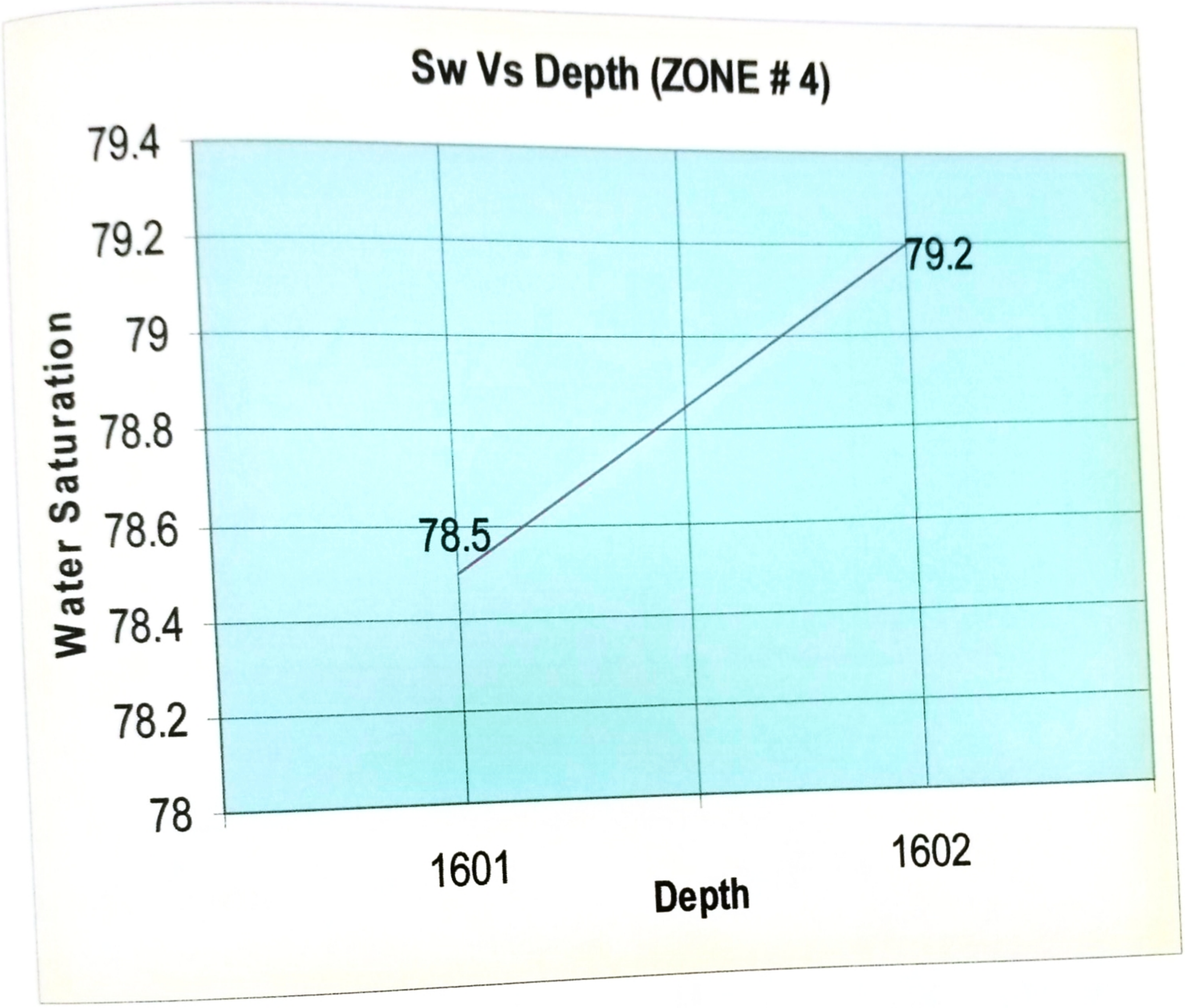

Figure 8.4: A graph between Sw and depth for Zone 4.

8.5 ZONE # 5 (1696-1698.5 m)

For zone 5, the computation of shale volume is given in Table 8.7 and the evaluation of porosity, Rt, S_w and S_h is given in Table 8.8. The graph plotted between Sw at the corresponding depth of zone 5 is shown in Figure 8.5.

Table 8.7: Basic shale volume evaluation by using gamma ray log.

DEPTH (m)	GR_{max} (GAPI)	GR_{min} (GAPI)	GR_{log} (GAPI)	V_{sh} (%)
1696	210	15	110	48.7
1697	210	15	75	30.7
1697.5	210	15	30	7.6
1698	210	15	45	15.3
1698.5	210	15	110	48.7

Table 8.8: Porosity, S_w and S_h calculations.

DEPTH (m)	RHOB (G/C3)	NPHI (V/V)	Rt (ohmm)	POROSITY (%)	S_w (%)	S_h (%)
1696	2.6	21	2.5	17	64.4	35.5
1697	2.75	11	7	8	81.8	18.2
1698	2.80	15	8	9	68.0	31.9

8.5.1 RESULT

In this zone, the shale volume is not high. Porosity is low to medium. But again the formation is water-wet as indicated by water saturation.

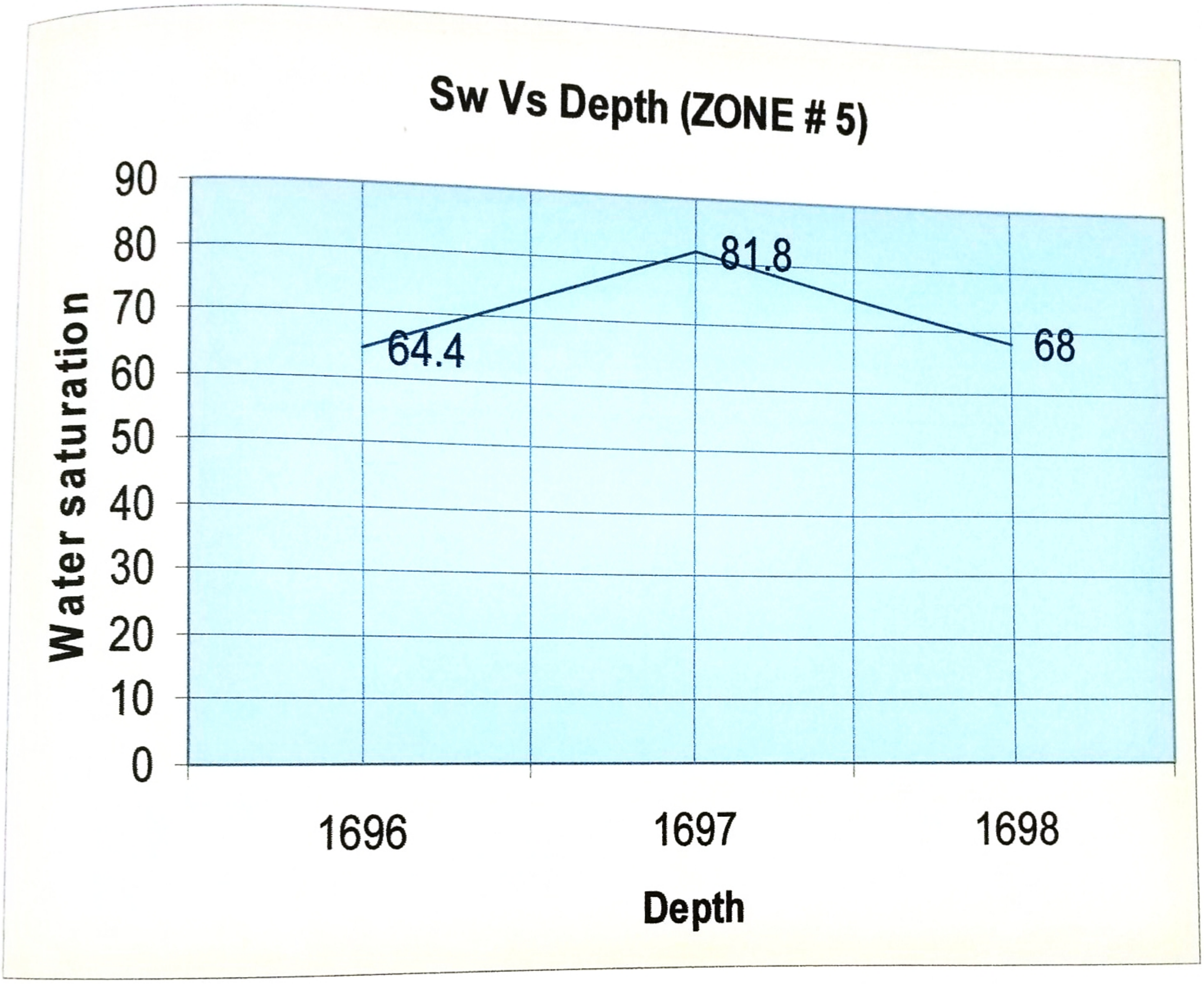

Figure 8.5: A graph between Sw and depth for Zone 5.

8.6 ZONE # 6 (1712-1718 m)

For zone 6, the computation of shale volume is given in Table 8.9 and the evaluation of porosity, Rt, S_w and S_h is given in Table 8.10. The graph plotted between Sw at the corresponding depth of zone 6 is shown in Figure 8.6.

Table 8.9: Basic shale volume evaluation by using gamma ray log.

DEPTH (m)	GR_{max} (GAPI)	GR_{min} (GAPI)	GR_{log} (GAPI)	V_{sh} (%)
1712	210	15	90	38.4
1713	210	15	20	2.56
1714	210	15	20	2.56
1715	210	15	25	5.12
1716	210	15	30	7.6
1717	210	15	18	1.5
1718	210	15	28	6.6

Table 8.10: Porosity, S_w and S_h calculations.

DEPTH (m)	RHOB (G/C3)	NPHI (V/V)	Rt (ohmm)	POROSITY (%)	S_w (%)	S_h (%)
1712	2.15	33	4	39	22.2	77.8
1713	2.77	7	28	5	65.2	34.8
1714	2.77	4	40	5	54.7	45.3
1715	2.67	9	9	9	64.1	35.9
1717	2.75	11	24	8	44.1	55.8

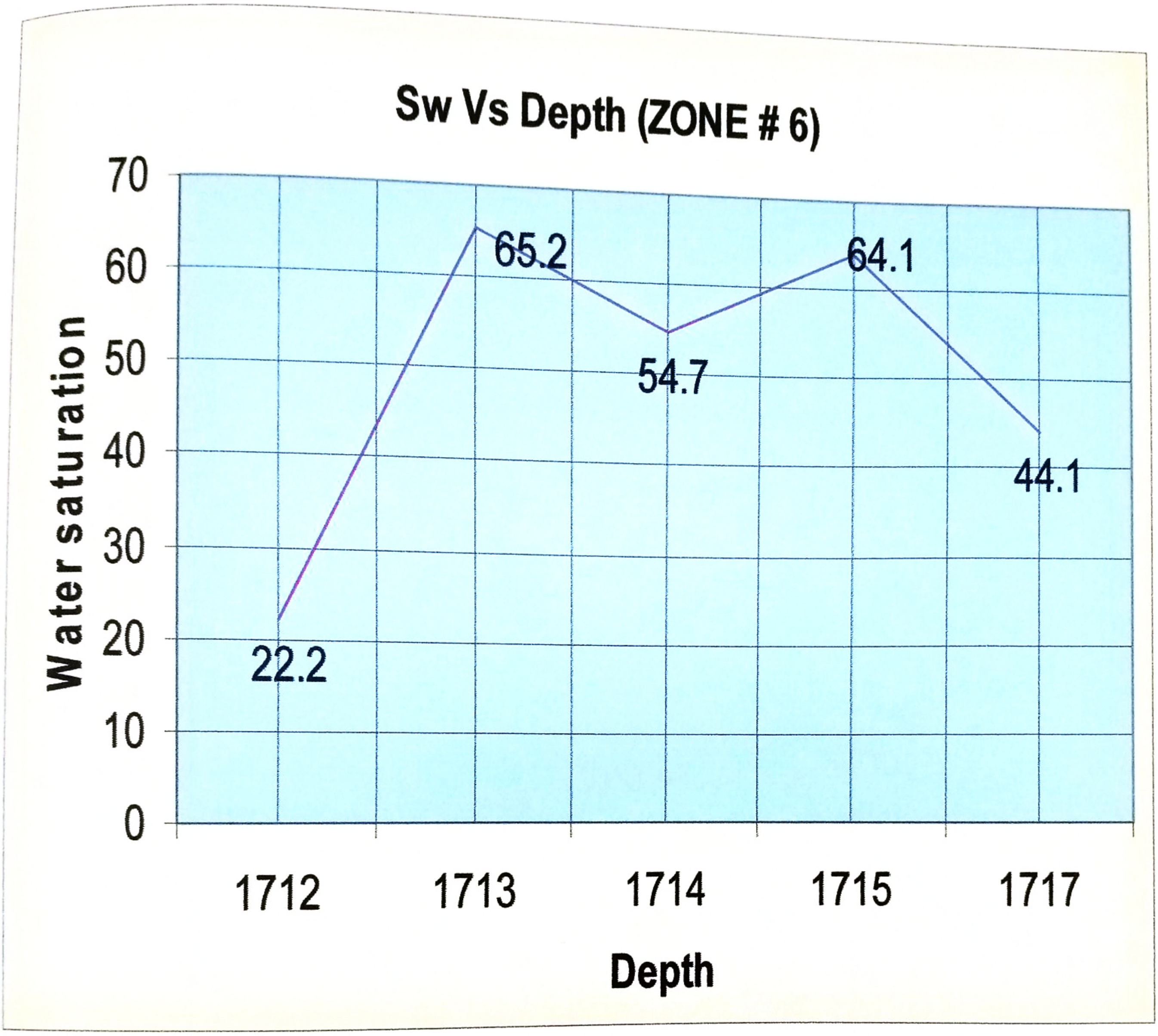

Figure 8.6: A graph between Sw and depth for Zone 6.

8.6.1 RESULT

In this zone the shale volume is very low indicating a good permeability. Although hydrocarbon saturation in this zone is good but RFT conducted at depth of 1714.5 meters gave a dry test result.

8.7 ZONE # 7 (1741-1747 m)

For zone 7, the computation of shale volume is given in Table 8.11 and the evaluation of porosity, Rt, S_w and S_h is given in Table 8.12. The graph plotted between Sw at the corresponding depth of zone 6 is shown in Figure 8.7.

Table 8.11: Basic shale volume evaluation by using gamma ray log.

DEPTH (m)	GR_{max} (GAPI)	GR_{min} (GAPI)	GR_{log} (GAPI)	V_{sh} (%)
1741	210	15	55	20.5
1742	210	15	30	7.6
1743	210	15	25	5.1
1744	210	15	25	5.1
1745	210	15	30	5.12
1746	210	15	25	5.1
1747	210	15	20	2.56

Table 8.12: Porosity, S_w and S_h calculations.

DEPTH (m)	RHOB (G/C3)	NPHI (V/V)	Rt (ohmm)	POROSITY (%)	S_w (%)	S_h (%)
1741	2.74	3	10	4	12.6	87.3
1742	2.65	12	7	10.5	27.7	72.2
1743	2.77	5	20	5	77.4	22.5
1744	2.67	9	9	9	64.1	35.9
1745	2.75	11	24	8	44.1	55.8

8.7.1 RESULT

In this zone the shale volume computation shows that it is quite low. Hydrocarbon saturation is also not low; porosity is low to medium.

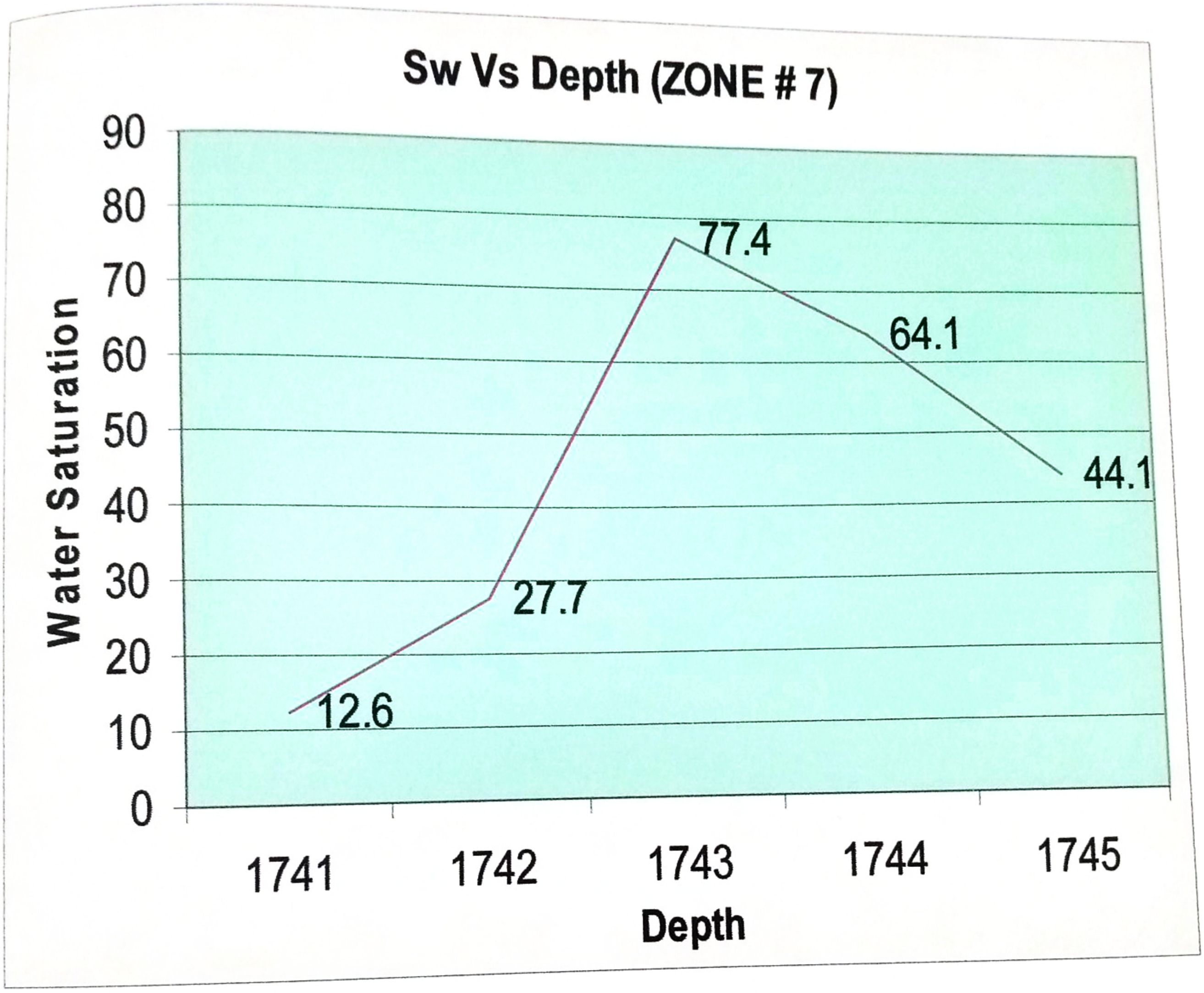

Figure 8.7: A graph between Sw and depth for Zone 7.

CHAPTER 9

CONCLUSION

9.1 POSSIBLE CAUSES OF FAILURE OF X-1

After drilling of X-1 and its being declared dry & abandoned preliminarily it can be concluded that.

1. Well X-1 was drilled on a basement involved high.
2. Before drilling of well the structural closure was anticipated up to the level of near top Salt Range formation.
3. After drilling of X-1 and running VSP the structural closure level looks to be near top of Kussak formation of Lower Cambrian age.
4. In X-1 the Basal sands have gross thickness of 10 meters, maximum core porosity is 14.4% to minimum 6.80% and average porosity is 10.7%. The permeabilities measured from the core are maximum 8.2 md and minimum 2.06 md.
5. The dolomite beds have Log porosities ranging from 3% to 6%. The upper Khewra sandstone have excellent porosities averging more than 15% all these objectives encountered have moderate to excellent reservoir quality and have good seals provided by shales. anhydrite and salt.
6. Review of the geochemical data of Salt Range Formation drilled by PSPD wells in the north, reveals that this formation has low source rock potential, having thin veinlets of black bituminous shales.
7. The geochemical investigation by G&R Lab shows the presence of good TOC values from 1450-1482 m in X-1 but layers of algal organic matter are very thin.
8. According to the geochemical analysis carried out by JNOC of Salt Range Formation in the Bahawalpur E-1, contains mainly type IV kerogen.
9. To the south across the border in India heavy crude oil has been discovered at Baghewala well. The oil may have migrated from a local source rock as the structure is located updip on a paleo high.
10. Dry hole in X-1 and absence of any gas shows during drilling may also indicate to the low source rock potential.

9.2 CONCLUSION

1. Good reservoir quality sands and dolomite are present in Cambrian sequence.

3. The well was drilled on a basement involved high with a sufficient structure closure.

4. The Geothermal gradient of the area is very low and as such oil window lies much below the Salt Range formation.

5. The possible cause of failure of X-1 well is the absence of any potential source rock with significant thickness and distribution & low geothermal gradient.

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